US009476648B2

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Sun et al.

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(45) **Date of Patent: Oct. 25, 2016**

(54) **SYSTEMS AND METHODS OF USING PHASE CHANGE MATERIAL IN POWER PLANTS**

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(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

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(22) Filed: **Jan. 21, 2015**

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Related U.S. Application Data

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(51) **Int. Cl.**
F28D 15/00 (2006.01)
F28D 1/02 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***F28D 1/0233*** (2013.01); ***B01F 3/0473*** (2013.01); ***F28D 20/023*** (2013.01); *F28C 3/10* (2013.01); *F28D 11/00* (2013.01)

(58) **Field of Classification Search**
CPC F28C 1/14; F28C 3/10; F28C 3/18; F28C 2001/006; F28F 25/06; F01K 9/003; F01K 9/00; F01K 9/02; F28D 1/0233; F28D 11/00; F28D 11/02; F28D 20/021; F28D 20/023; F28D 20/025; F24F 3/1423; B01J 8/386; B01F 3/0473
USPC 165/104.17, 900, 6, 7, 8, 104.18
See application file for complete search history.

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Assistant Examiner — Jon T Schermerhorn
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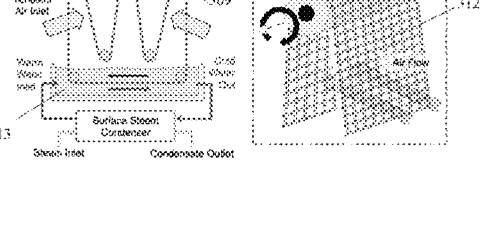
(57) **ABSTRACT**

Cooling systems and methods for cooling in a power plant using a phase change material. In one embodiment, a phase change material container includes at least one phase change material which may be in the form of a slurry; and at least one conduit for transporting the fluid through the phase change material when located in the phase change material container. The system may also comprise an air flow chamber; and a phase change material flow system including a pump for pumping phase change material from an outlet of phase change material container, to at least one phase change material spray nozzle. The phase change material flow system is configured to ensure that solidified phase change material is returned to the phase change material container.

4 Claims, 23 Drawing Sheets



(51) **Int. Cl.**

F28D 20/02	(2006.01)
B01F 3/04	(2006.01)
F28D 11/00	(2006.01)
F28C 3/10	(2006.01)

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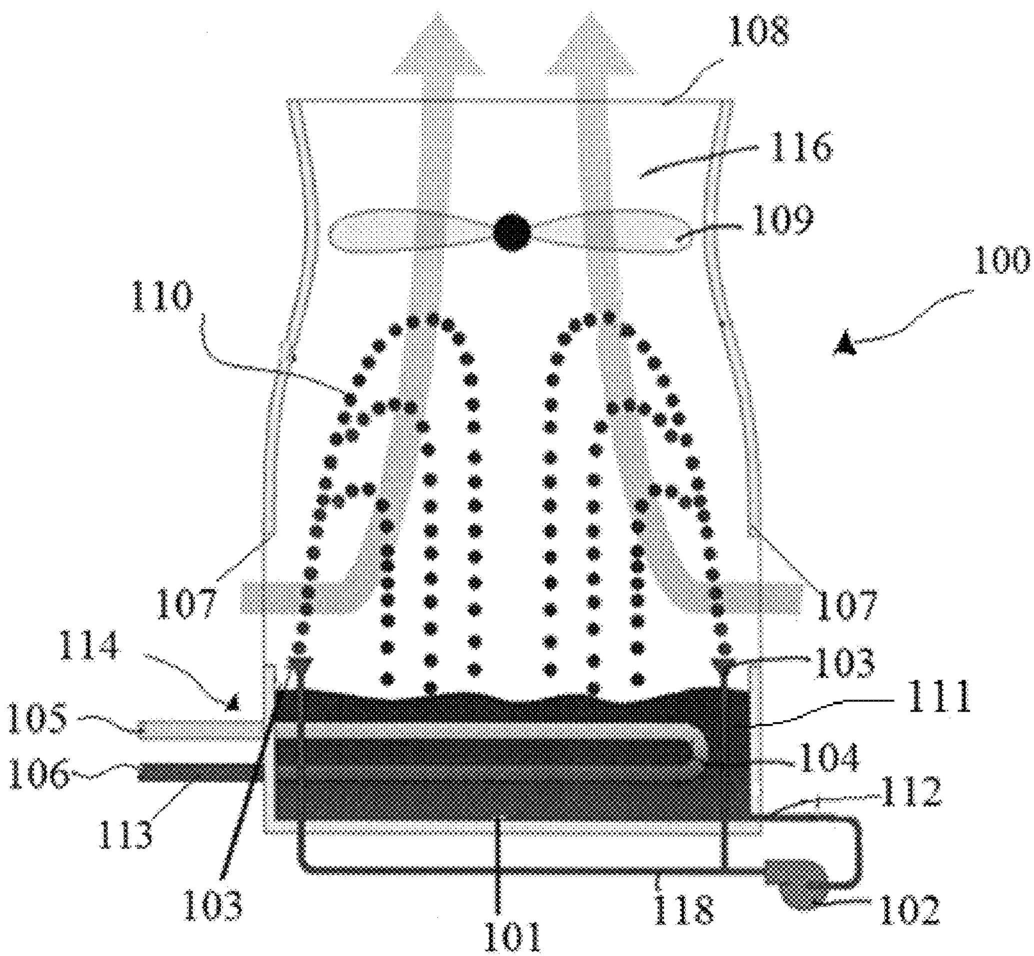

108
116
109
100
110
107
107
114
103
111
105
104
106
112
113
103
118
102
101

FIG. 1

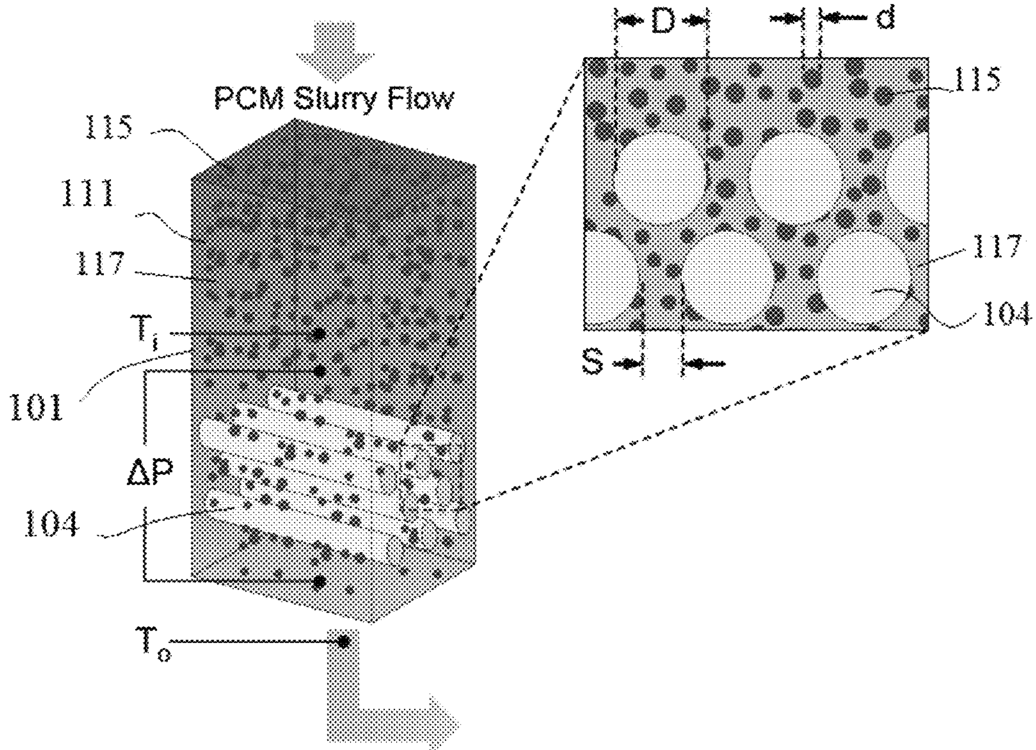


FIG. 2

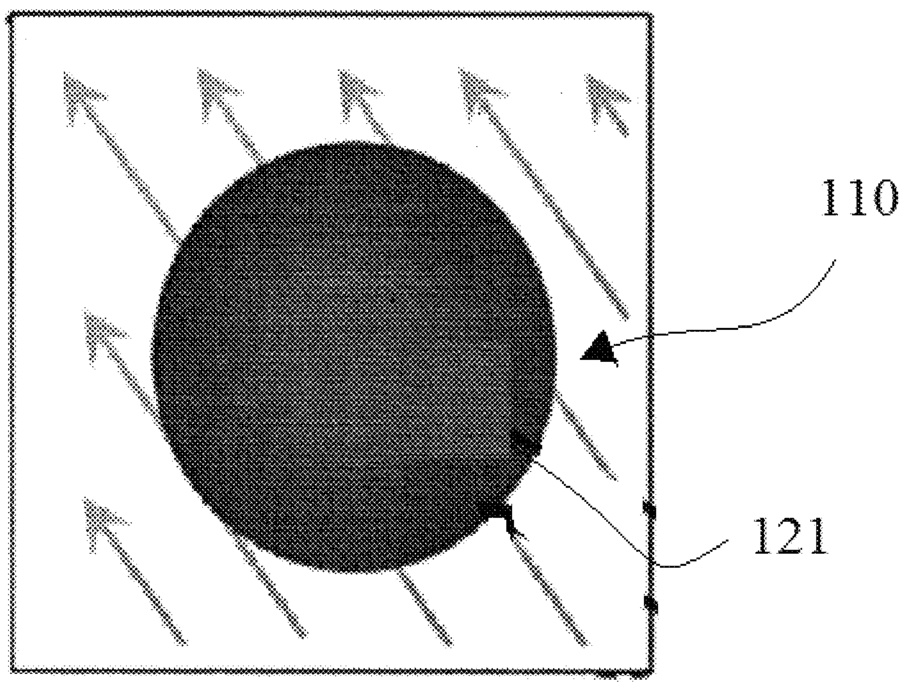


FIG. 3

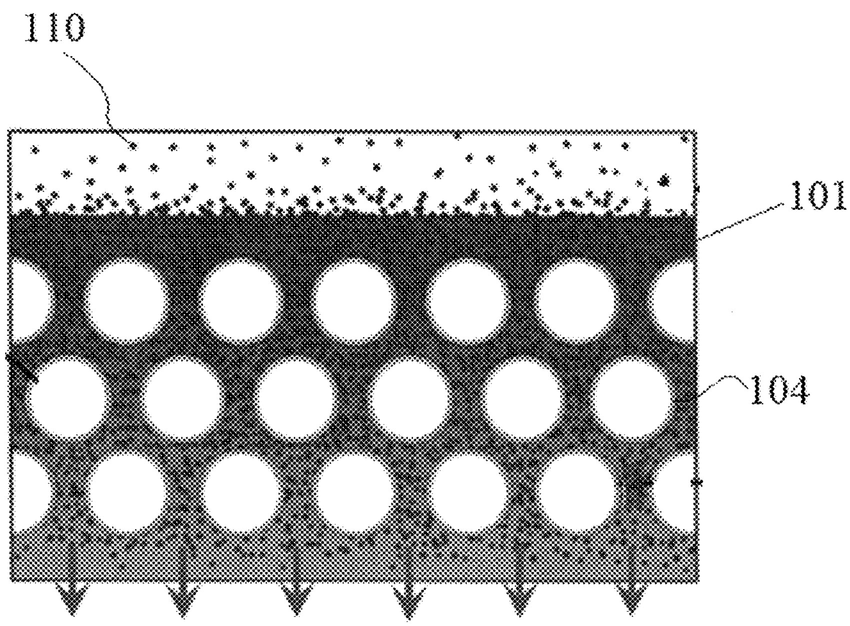

110
101
104

FIG. 4

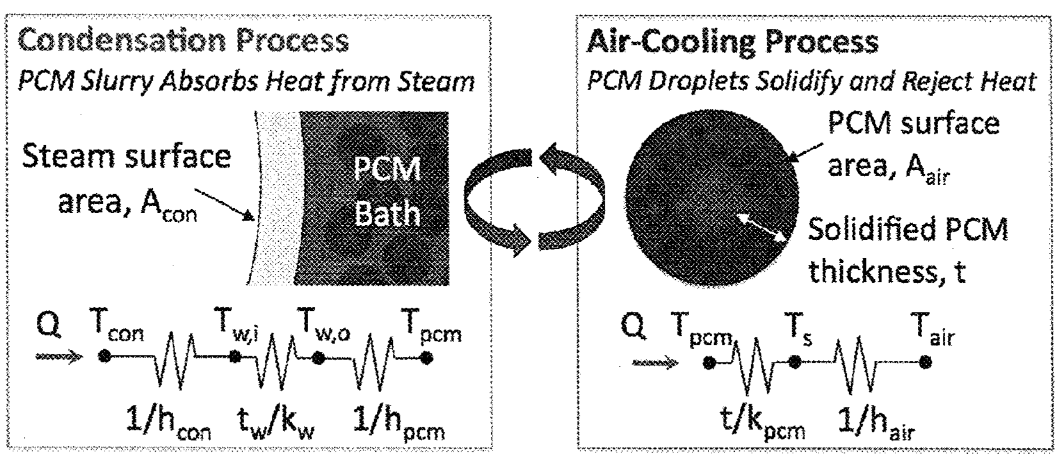

Condensation Process
PCM Slurry Absorbs Heat from Steam
Steam surface area, A_{con}
PCM Bath
Q
T_{con}
$T_{w,i}$
$T_{w,o}$
T_{pcm}
$1/h_{con}$
t_w/k_w
$1/h_{pcm}$
Air-Cooling Process
PCM Droplets Solidify and Reject Heat
PCM surface area, A_{air}
Solidified PCM thickness, t
Q
T_{pcm}
T_s
T_{air}
t/k_{pcm}
$1/h_{air}$

FIG. 5

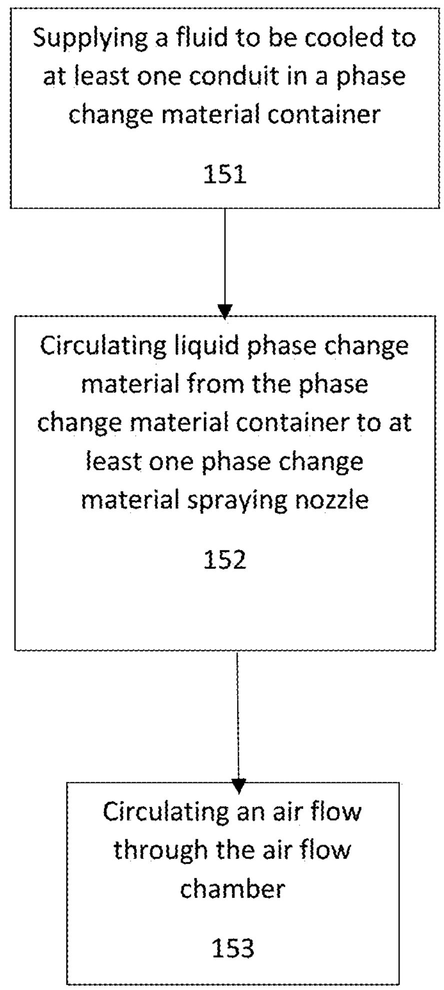

Supplying a fluid to be cooled to at least one conduit in a phase change material container
151
Circulating liquid phase change material from the phase change material container to at least one phase change material spraying nozzle
152
Circulating an air flow through the air flow chamber
153

FIG. 6

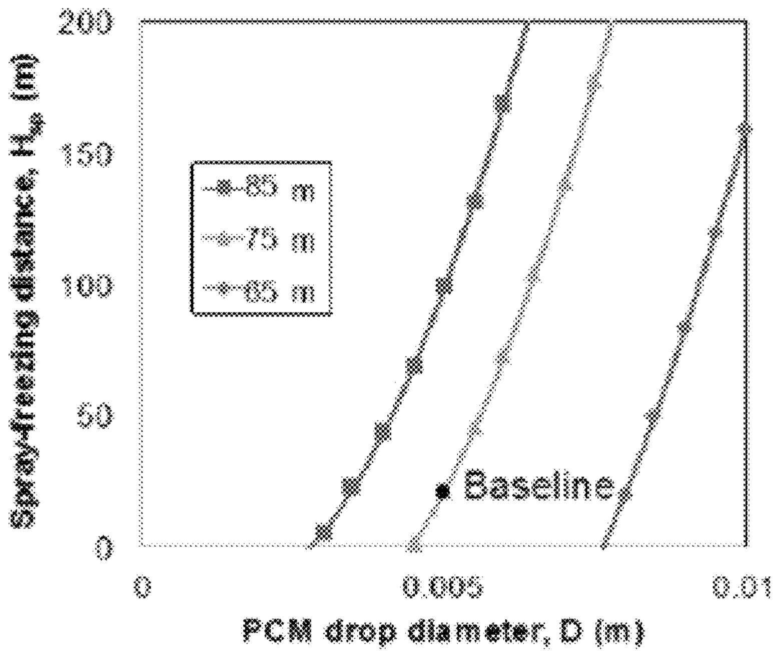

200
150
100
50
0
0
0.005
0.01
Spray-freezing distance, H_{sp} (m)
PCM drop diameter, D (m)
85 m
75 m
65 m
Baseline

FIG. 7

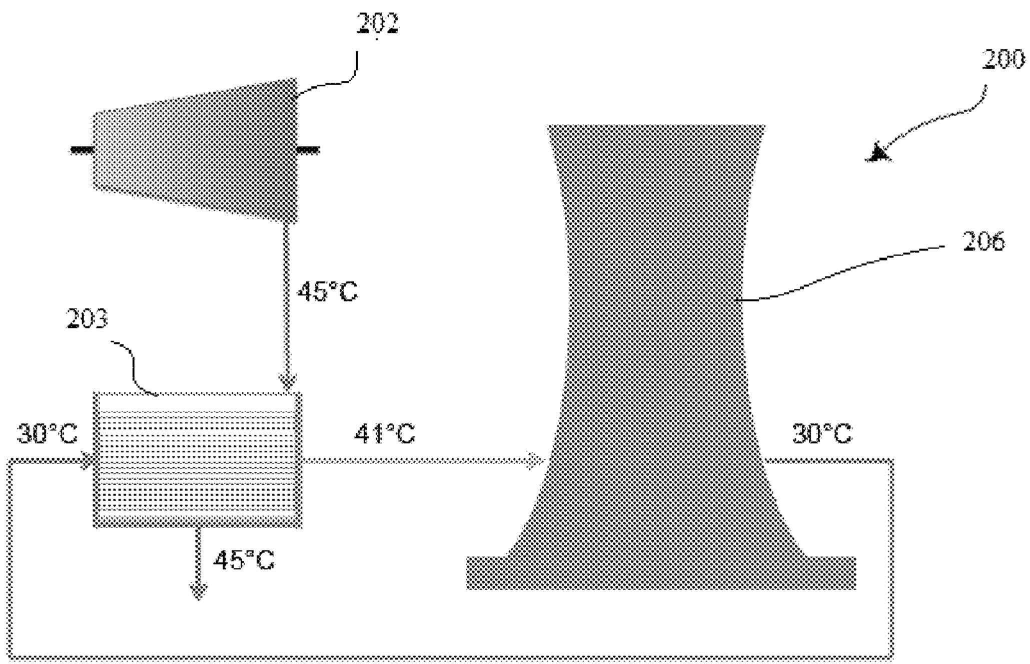


FIG. 8

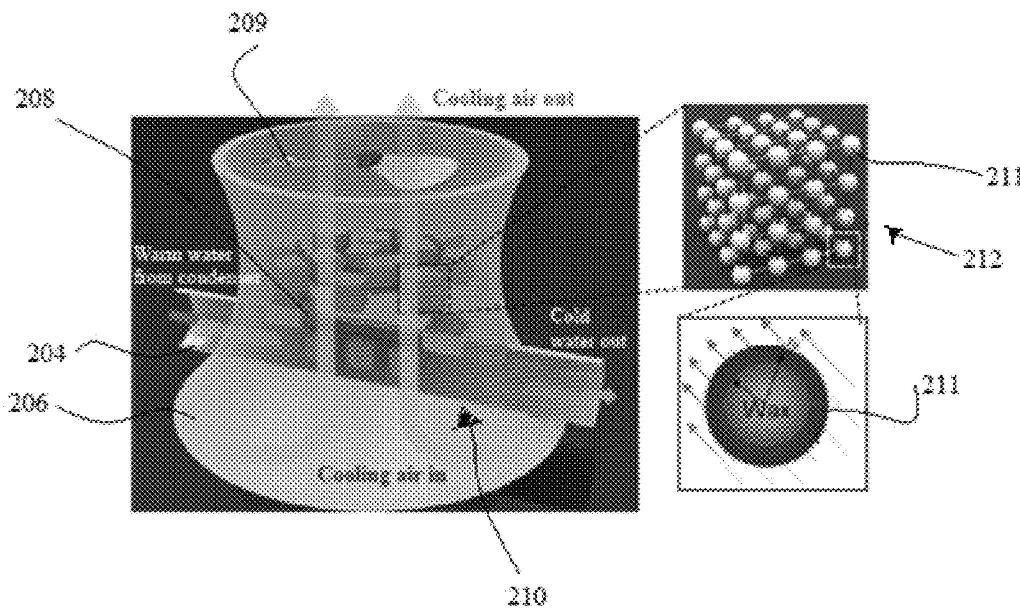

209
208
Cooling air out
Warm water from condenser
Cold water out
204
206
Cooling air in
210
211
212
211
Water

FIG. 9

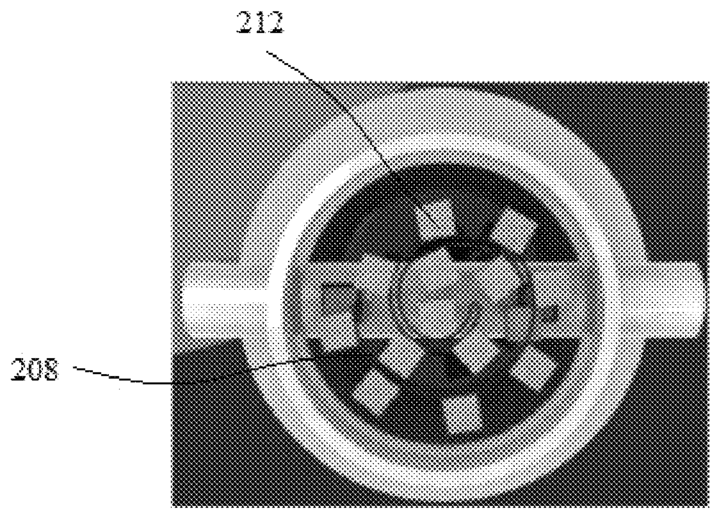


FIG. 10

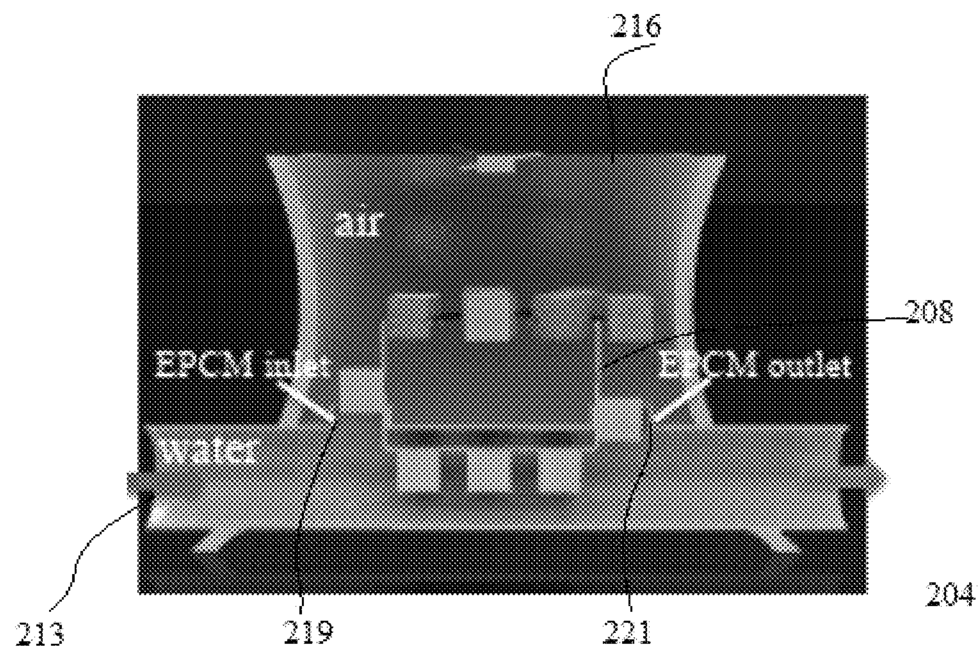

216
air
208
EPCM inlet
EPCM outlet
water
204
213
219
221

FIG. 11

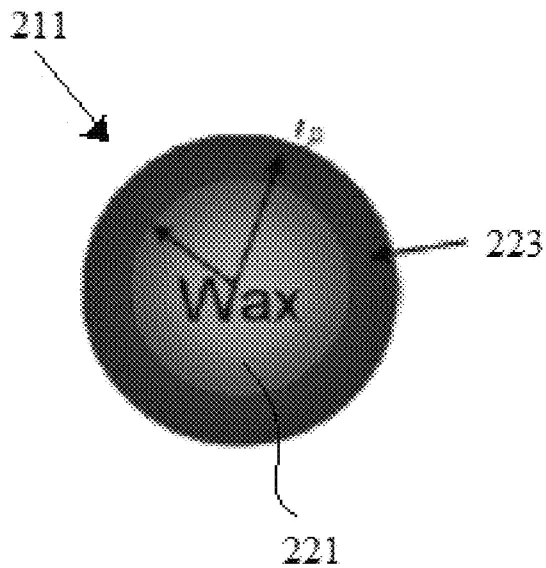
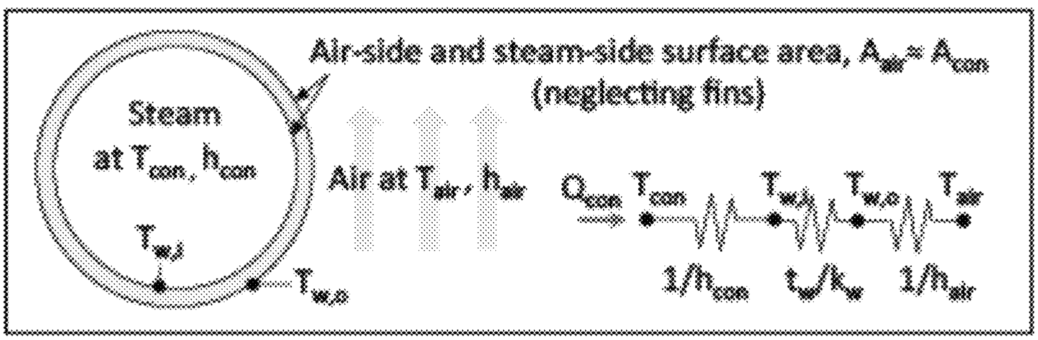

211
223
Wax
221

FIG. 12



Air-side and steam-side surface area, $A_{air} \approx A_{con}$
(neglecting fins)
Steam
at T_{con}, h_{con}
Air at T_{air}, h_{air}
$T_{w,i}$
$T_{w,o}$
Q_{con}
T_{con}
$T_{w,i}$
$T_{w,o}$
T_{air}
$1/h_{con}$
t_w/k_w
$1/h_{air}$

FIG. 13

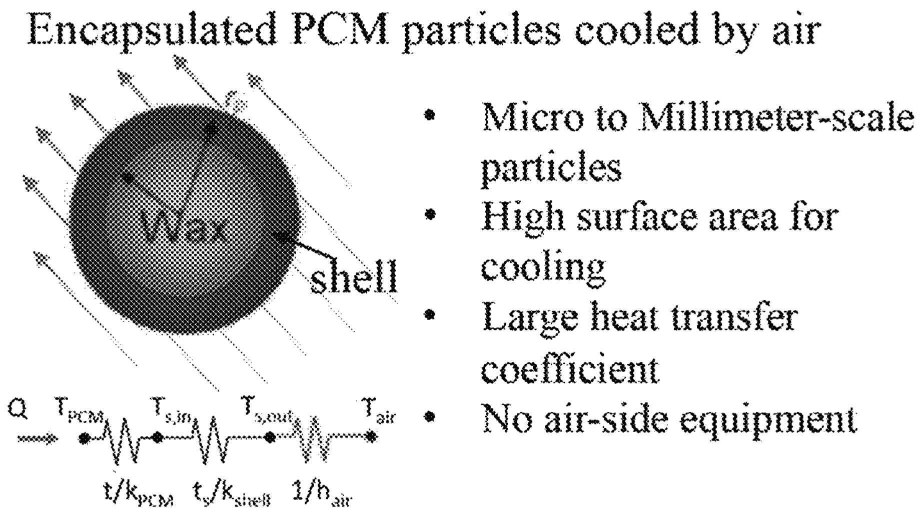

Encapsulated PCM particles cooled by air
Wax
shell
Q
T_{PCM}
$T_{s,in}$
$T_{s,out}$
T_{air}
t/k_{PCM}
t_s/k_{shell}
$1/h_{air}$
• Micro to Millimeter-scale particles
• High surface area for cooling
• Large heat transfer coefficient
• No air-side equipment

FIG. 14

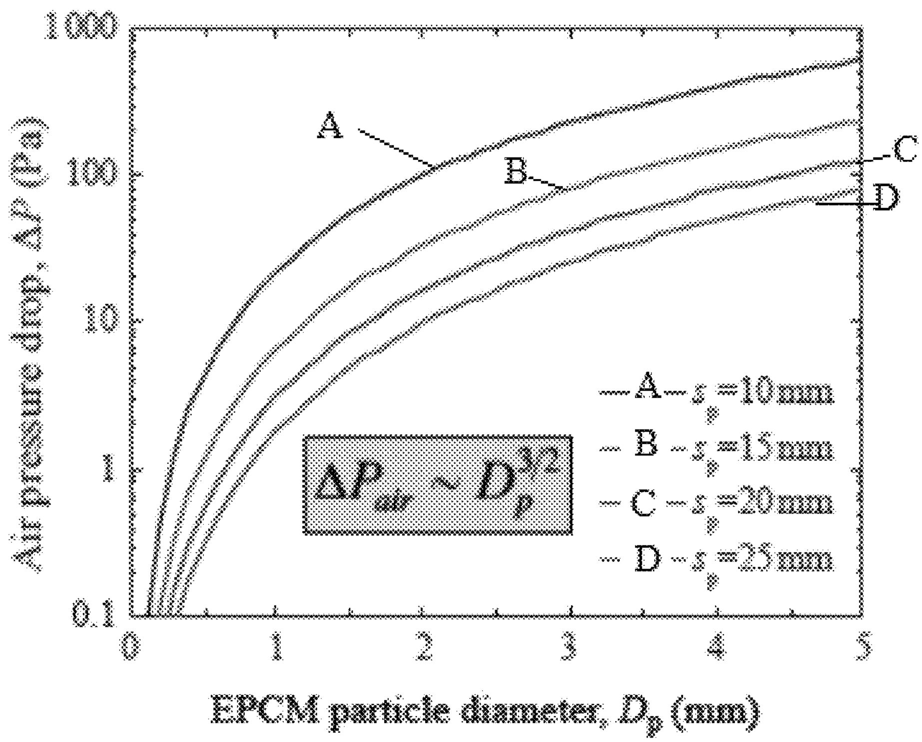
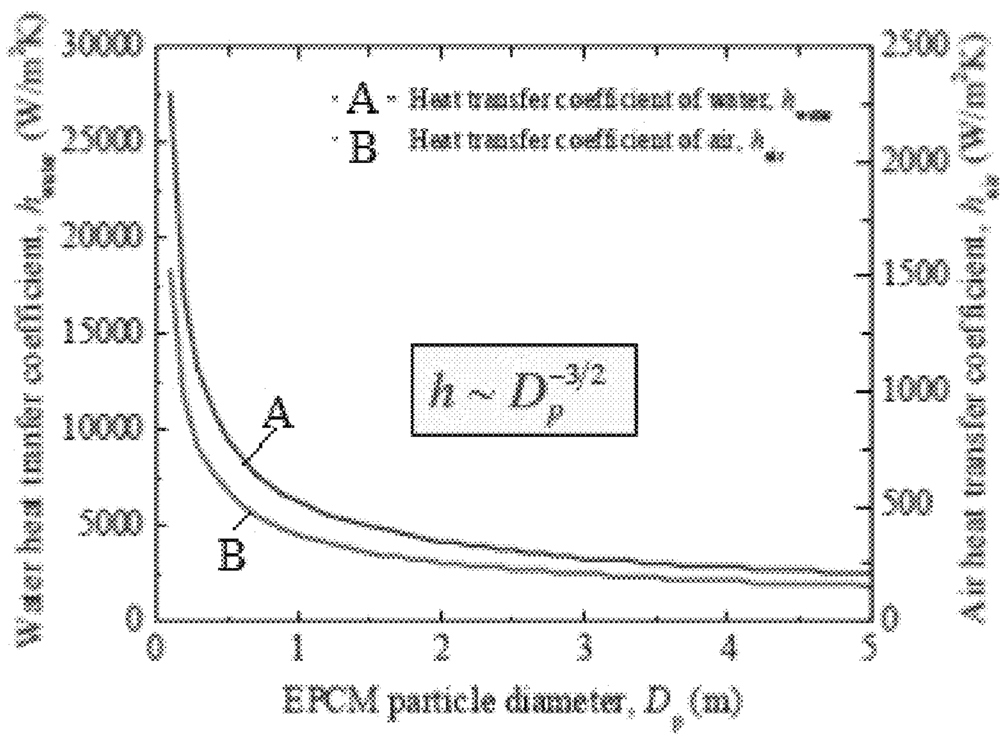

Air pressure drop, ΔP (Pa)
1000
100
10
1
0.1
0
1
2
3
4
5
EPCM particle diameter, D_p (mm)
A
B
C
D
$\Delta P_{air} \sim D_p^{3/2}$
A s_p=10 mm
B s_p=15 mm
C s_p=20 mm
D s_p=25 mm

FIG. 15



Water heat transfer coefficient, h_{water} (W/m^{2}K)
Air heat transfer coefficient, h_{air} (W/m^{2}K)
EPCM particle diameter, D_p (m)
A - Heat transfer coefficient of water, h_{water}
B - Heat transfer coefficient of air, h_{air}
$h \sim D_p^{-3/2}$
A
B
30000
25000
20000
15000
10000
5000
0
2500
2000
1500
1000
500
0
0
1
2
3
4
5

FIG. 16

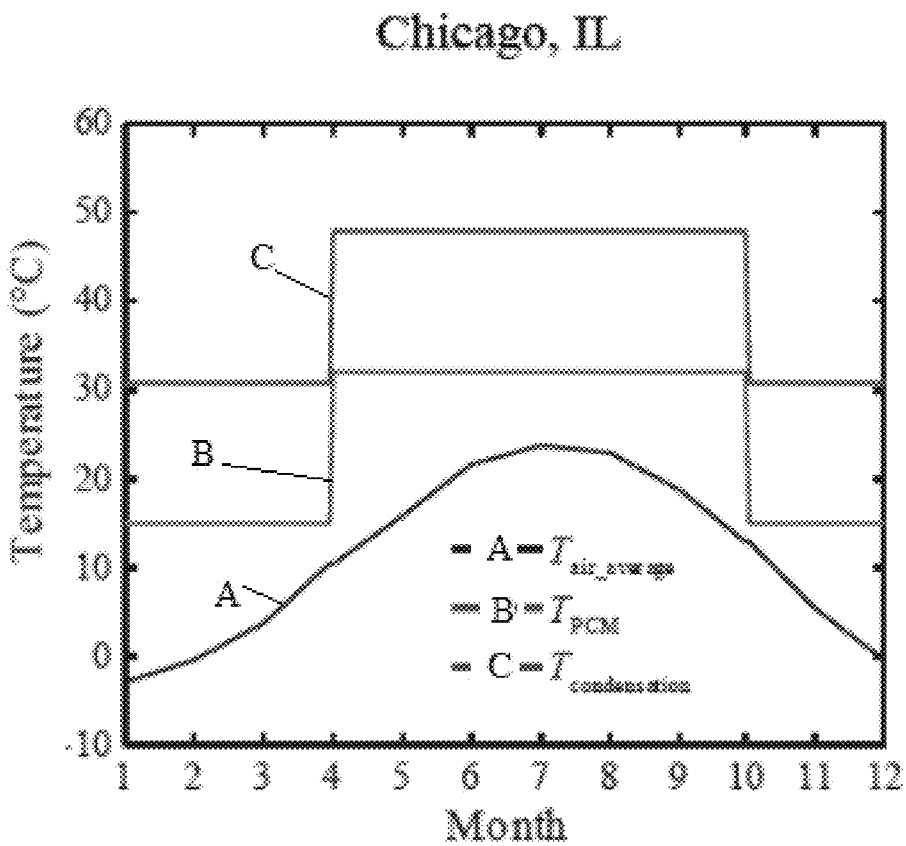

Chicago, IL
Temperature (°C)
Month
60
50
40
30
20
10
0
-10
1
2
3
4
5
6
7
8
9
10
11
12
C
B
A
A
B
C

FIG. 17

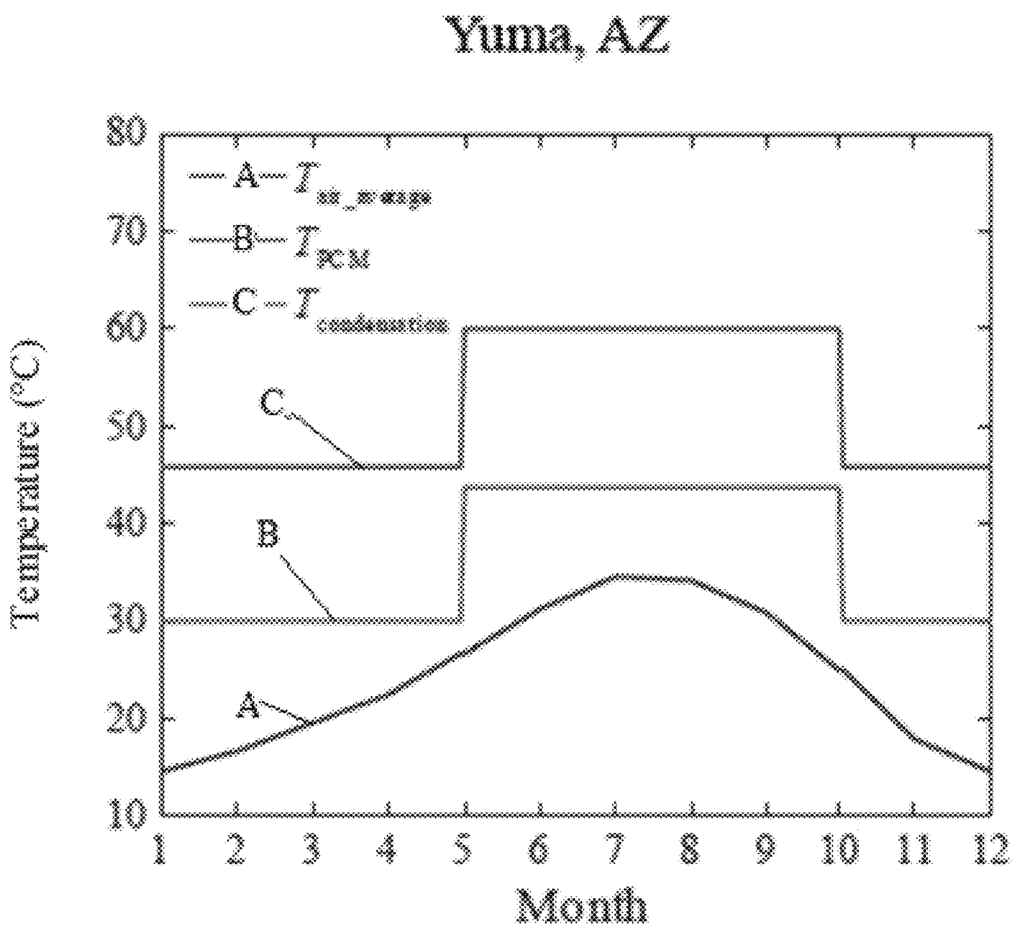

Yuma, AZ
A
B
C
80
70
60
50
40
30
20
10
Temperature (°C)
1
2
3
4
5
6
7
8
9
10
11
12
Month

FIG. 18

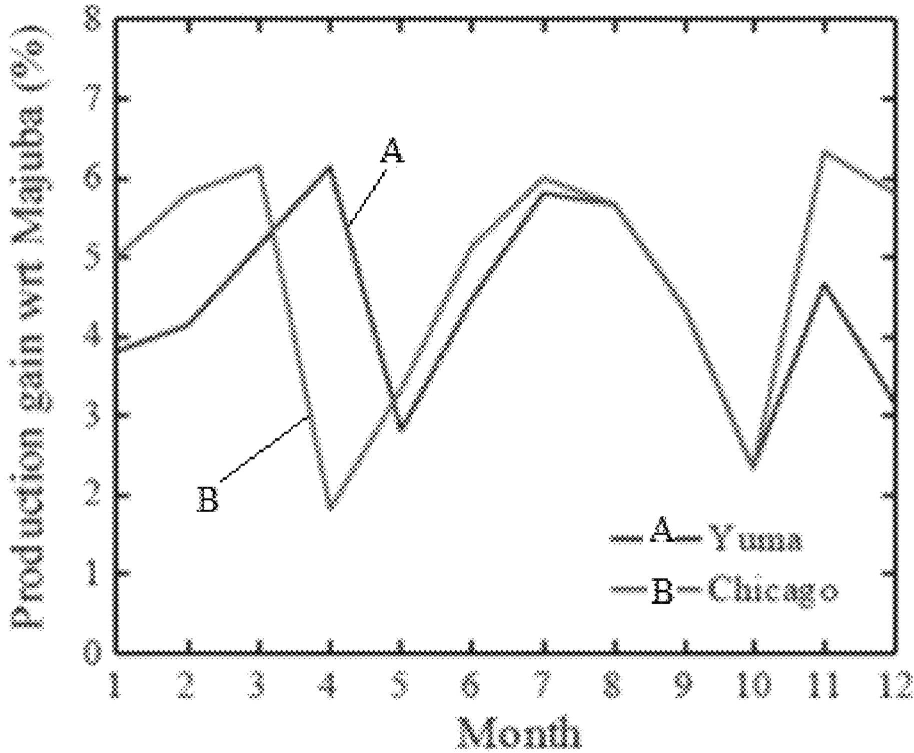

Production gain wrt Majuba (%)
8
7
6
5
4
3
2
1
0
1
2
3
4
5
6
7
8
9
10
11
12
Month
A
B
A Yuma
B Chicago

FIG. 19

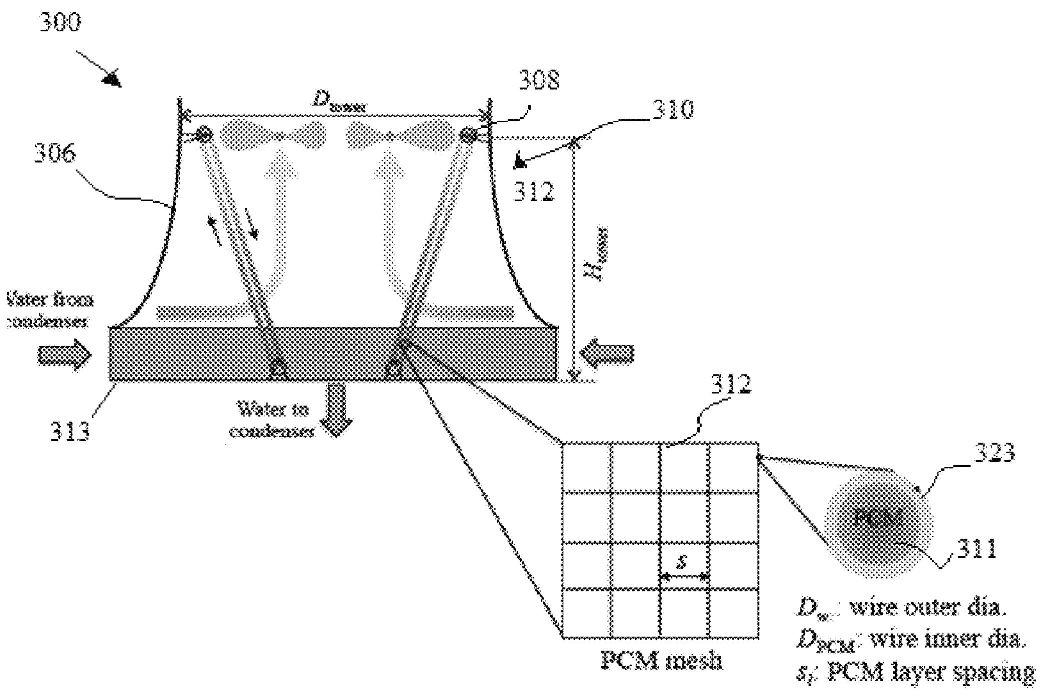

300
308
310
312
306
Water from condenser
313
Water to condenser
312
323
PCM
311
PCM mesh
D_w: wire outer dia.
D_{PCM}: wire inner dia.
s_l: PCM layer spacing

FIG. 20

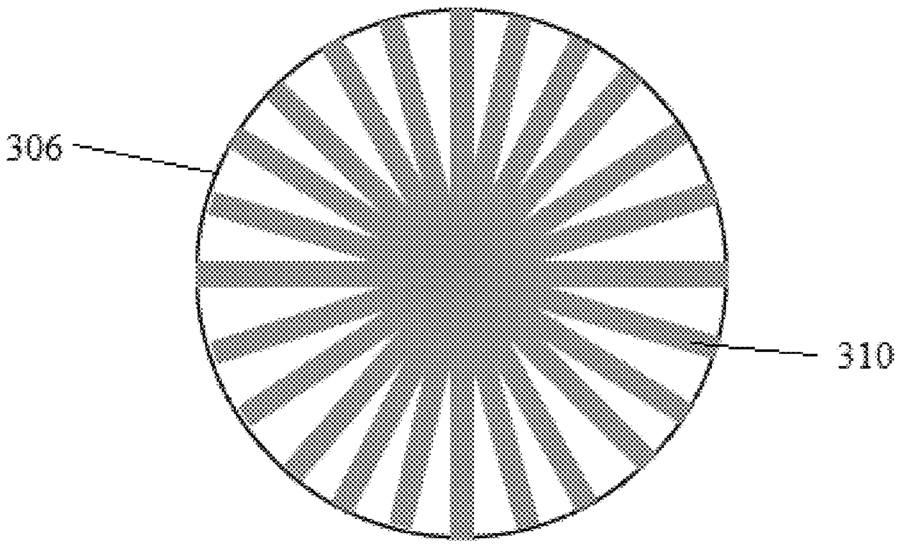


FIG. 21

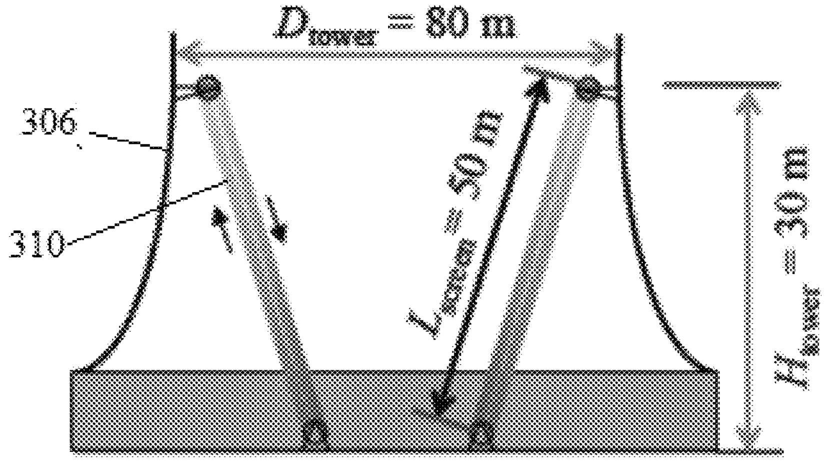


FIG. 22

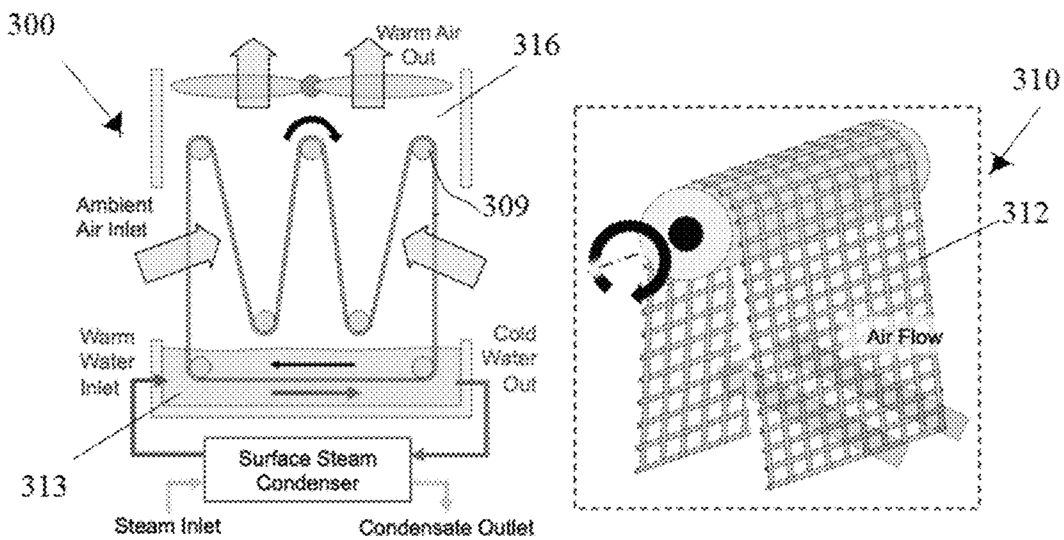
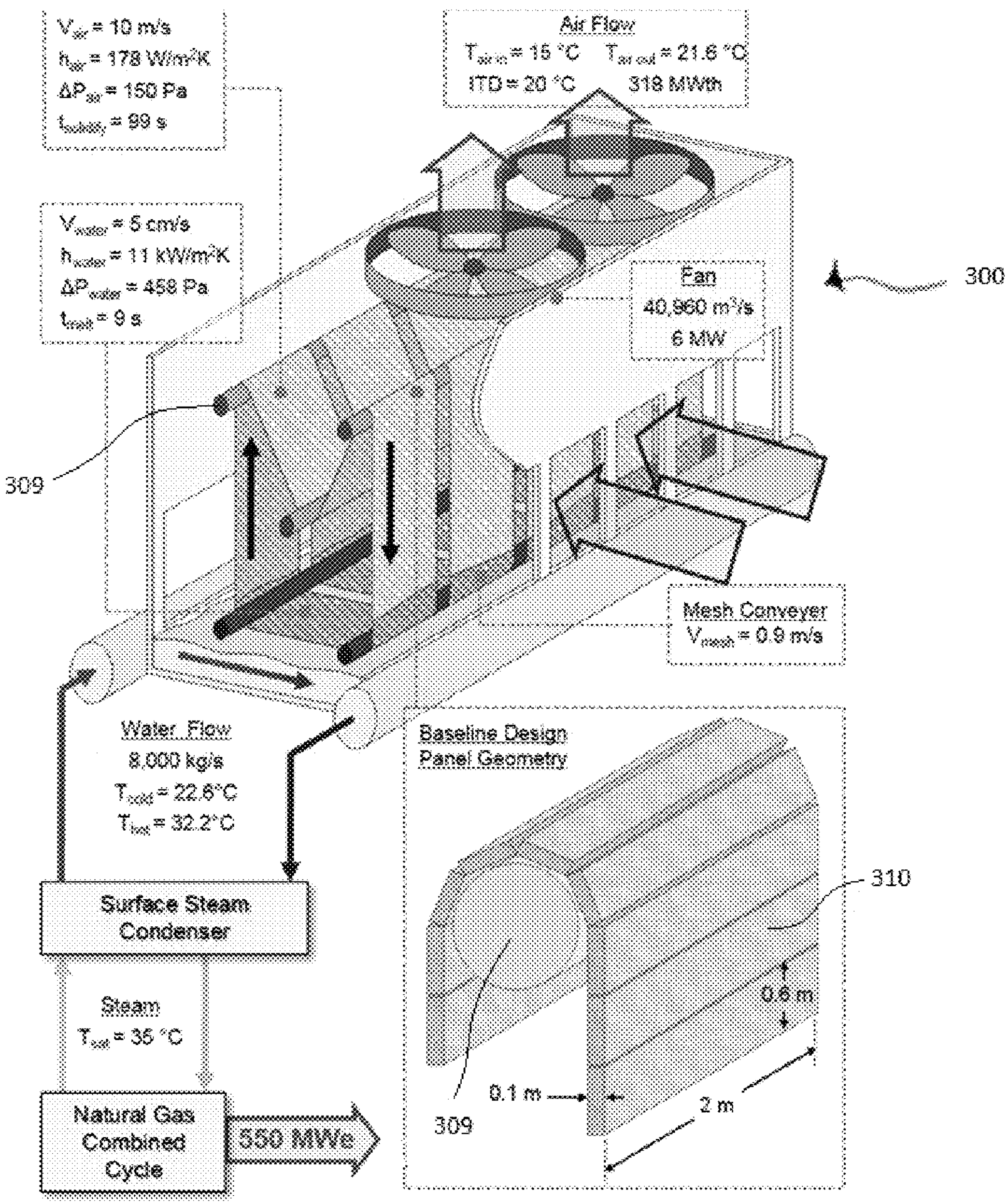

300
Warm Air
Out
316
310
309
Ambient
Air Inlet
312
Air Flow
Warm
Water
Inlet
Cold
Water
Out
313
Surface Steam
Condenser
Steam Inlet
Condensate Outlet

FIG. 23



V_{air} = 10 m/s
h_{air} = 178 W/m²K
ΔP_{air} = 150 Pa
$t_{subsity}$ = 99 s
Air Flow
$T_{air\,in}$ = 15 °C $T_{air\,out}$ = 21.6 °C
ITD = 20 °C 318 MWth
V_{water} = 5 cm/s
h_{water} = 11 kW/m²K
ΔP_{water} = 458 Pa
t_{melt} = 9 s
Fan
40,960 m³/s
6 MW
300
309
Mesh Conveyer
V_{mesh} = 0.9 m/s
Water Flow
8,000 kg/s
T_{cold} = 22.6°C
T_{hot} = 32.2°C
Baseline Design
Panel Geometry
310
Surface Steam Condenser
Steam
T_{sat} = 35 °C
0.6 m
0.1 m
2 m
309
Natural Gas Combined Cycle
550 MWe

FIG. 24

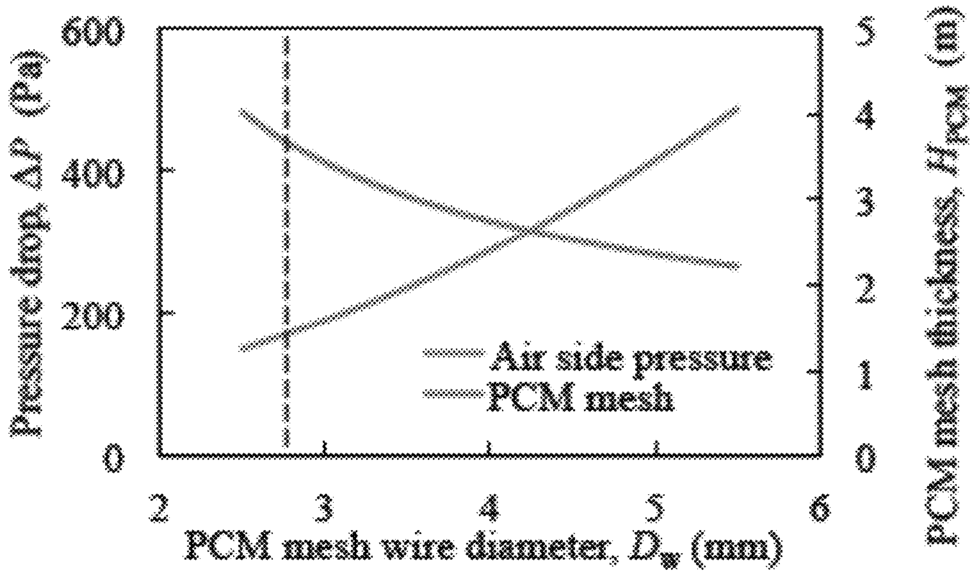

Pressure drop, ΔP (Pa)
600
400
200
0
2
3
4
5
6
PCM mesh wire diameter, D_w (mm)
5
4
3
2
1
0
PCM mesh thickness, H_{PCM} (m)
Air side pressure
PCM mesh

FIG. 25

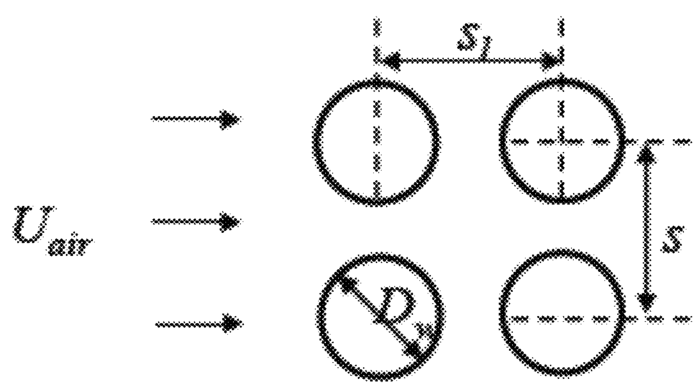
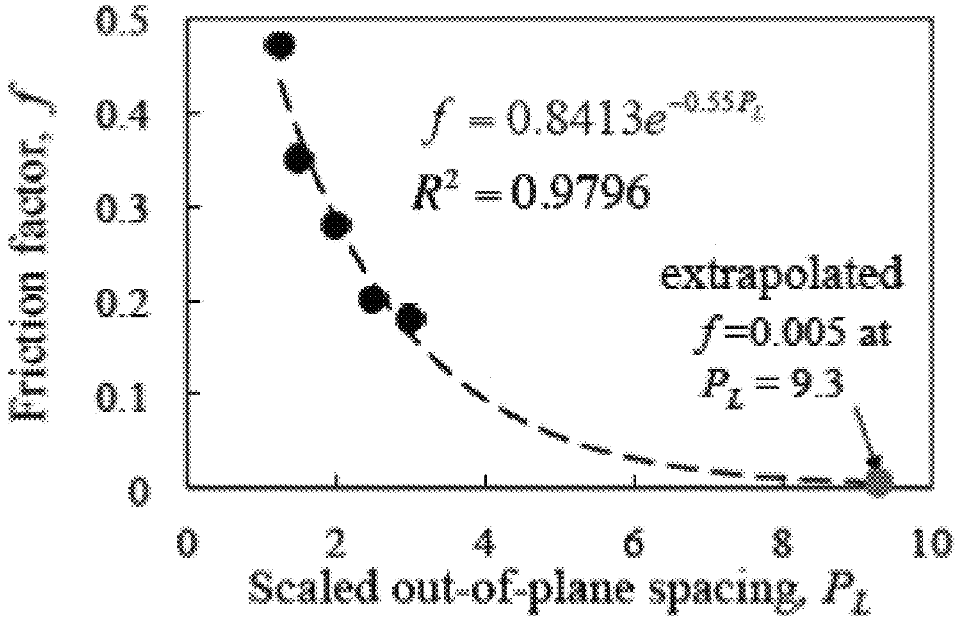

S_l
U_{air}
S
D_w

FIG. 26



0.5
0.4
0.3
0.2
0.1
0
Friction factor, f
$f = 0.8413e^{-0.55P_L}$
$R^2 = 0.9796$
extrapolated
f=0.005 at
$P_L = 9.3$
0
2
4
6
8
10
Scaled out-of-plane spacing, P_L

FIG. 27

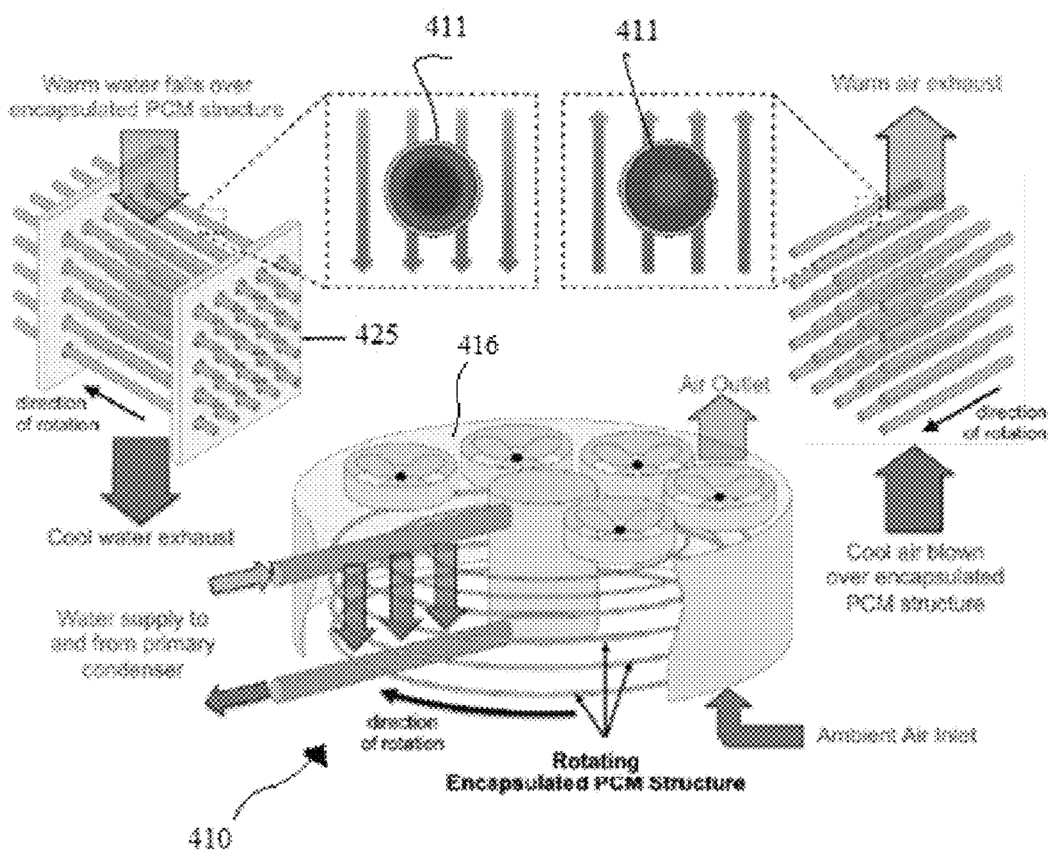

411
411
Warm water falls over encapsulated PCM structure
Warm air exhaust
425
416
Air Outlet
direction of rotation
direction of rotation
Cool water exhaust
Cool air blown over encapsulated PCM structure
Water supply to and from primary condenser
direction of rotation
Rotating Encapsulated PCM Structure
Ambient Air Inlet
410

FIG. 28

SYSTEMS AND METHODS OF USING PHASE CHANGE MATERIAL IN POWER PLANTS

RELATED APPLICATION DATA

This application claims the benefit of U.S. Provisional Application No. 61/929,747, filed on Jan. 21, 2014, the contents of which are herein incorporated by reference.

STATEMENT OF GOVERNMENT INTEREST

This invention was made with government support under Grant No. 1357918 by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is directed to the field of power plants. In particular, the present invention is directed to systems and methods for cooling a power plant using phase change materials.

The cooling towers for power plants generally consume a large amount of water. For example, in the year 2000, coal and gas power plants in the eight-state Interior West region of the United States withdrew over 650 million gallons of water per day, totaling over 728,000 acre-feet each year. That is enough water for the annual needs of at least 3.64 million people. Water in the West of the United States is becoming increasingly valuable especially in light of widespread drought conditions.

2. Description of Related Technology

Although agriculture is the largest water user in most of the United States, power production can have a large impact on the water supply and water quality in specific locations, especially in river basins that are already over-extended with other water uses. Large amounts of research have been devoted to design a cooling tower with a higher cooling efficiency and to reduce water consumption. For example, U.S. Patent Application Publication No. 2010/0018237 discloses a low water consumption cooling tower for gasification plants. The cooling tower comprises a wet section having a plurality of wet section fans and a dry section having a plurality of dry section fans. The wet section fans are adjustable to operate at different rates, depending upon ambient conditions surrounding the cooling tower. The wet section may comprise at least one shutter door. In operation, the wet section fans typically operate at an increased rate during a summer peak price period and at a reduced rate during a winter peak price period and an off-peak price period. The dry section fans operate at the increased rate all year. This method allows for less evaporative cooling and more latent cooling thereby reducing water consumption.

U.S. Patent Application Publication No. 2010/0154406 discloses a cooling tower system that exhibits increased energy efficiency. The cooling tower system includes a cooling tower unit, an expansion engine and a power operated component such as a fan or pump. The process fluid is first used to heat a working fluid for an expansion engine before being sent to the cooling tower for cooling. Power generated by the expansion engine is utilized to operate a component of the cooling tower such as a fan or a pump. The cooling tower is also utilized to provide cooling to condense the working fluid from vapor to liquid. The cooling tower removes waste heat from the process fluid.

U.S. Patent Application Publication No. 2013/0000867 discloses a hybrid cooling system for condensing an exhaust stream of a steam turbine. The cooling system comprises a dry cooling circuit, a dry air-cooled unit performing heat dissipation to cooling water flowing therein, and a wet cooling circuit and a wet cooled unit performing heat dissipation to the cooling water flowing therein. The cooling water flowing in the dry cooling circuit is separated from the cooling water flowing in the wet cooling circuit, and the dry and wet cooling circuits are connected to a common condenser. The hybrid cooling system reduces the evaporation and deposition losses of the wet cooling system, thereby reducing water consumption.

EP 2 498 037 A2 discloses a hybrid fan cooling tower apparatus that extends along a vertical axis. The cooling tower includes a first housing structure having an inlet and a first outlet located at a first position along the vertical axis, wherein the housing structure includes a base and opposing side walls that extend along the vertical axis away from the base. The tower also includes a heat exchanger disposed in the housing structure. The heat exchanger is positioned adjacent the first outlet and extends at least partially across the first outlet. The hybrid tower employs an air current generator positioned in a plane normal to the vertical axis and oriented to direct an air stream toward the base and through the heat exchanger and the first outlet.

Even with these improved cooling tower designs from the prior art, water consumption is still a major disadvantage for power plants throughout the world. The reliance on water places constraints on the location of power plants, which is currently limited to areas near a large body of water. Unfortunately, these areas are also densely populated, creating safety and pollution concerns. A cooling tower that reduces or eliminates water consumption will enable building of power plants in remote areas with little water available which are poorly suited for human living and agriculture.

SUMMARY OF THE INVENTION

An aspect of the invention may be a cooling system for cooling a fluid, comprising: a phase change material container housing at least one phase change material; at least one conduit for transporting said fluid passing through said phase change material; an air flow chamber; a device for generating an air flow through the air flow chamber; an air flow outlet fluidly connected to said air flow chamber for removing heated air from said cooling system; and a phase change material flow system for circulating phase change material from said phase change material container via said air flow chamber and back to said phase change material container.

Another aspect of the invention may be a method for operating a cooling system for cooling a fluid, comprising steps of: transferring heat from the fluid to a phase change material to melt at least some of the phase change material to provide liquid phase change material; spraying droplets containing said liquid phase change material into circulating air for cooling and solidifying at least some of the liquid phase change material to provide solid phase change material by heating said air to provide heated air; recycling the solid phase change material to the transferring step; and removing the heated air from the cooling system

Still yet another aspect of the invention may be a cooling system for cooling a fluid, comprising a heat exchanger including an encapsulated phase change material, wherein heat is transferred from the fluid to an encapsulated phase change material to melt at least some of the phase change material therein.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a schematic representation of a cooling system according to one embodiment of the present invention.

FIG. **2** is a schematic representation of phase change material slurry flow and heat transfer characteristics in the phase change material.

FIG. **3** shows a phase change material droplet in an air flow within an air flow chamber of the cooling system of the present invention.

FIG. **4** is a schematic representation of a phase change material container with conduits and containing a phase change material.

FIG. **5** depicts decoupled steam condensation and air cooling in accordance with the present invention.

FIG. **6** is a flow chart of a method for operating a cooling system for cooling a fluid, according to one embodiment of the present invention.

FIG. **7** shows the relationship between spray-freezing distance vs. phase change material droplet diameter in a computer simulated model.

FIG. **8** is a schematic diagram of the power plant cooling system in accordance with an embodiment of the invention.

FIG. **9** is a schematic diagram of the cooling system using an encapsulated phase change material.

FIG. **10** is a top down view of the cooling system shown in FIG. **9**.

FIG. **11** is an interior diagram of a portion of the cooling system shown in FIG. **9** using the encapsulated phase change material.

FIG. **12** is a diagram of an encapsulated phase change material.

FIG. **13** is a diagram of a conventional air cooled steam tube.

FIG. **14** is a diagram showing a cooled encapsulated phase change material particle.

FIG. **15** is a graph showing air pressure drop versus encapsulated particle diameter for varying center-to-center particle spacings.

FIG. **16** is a graph of the encapsulated phase change material particle diameter as it relates to the water heat transfer coefficient and the air heat transfer coefficient.

FIG. **17** is a graph showing the annual temperatures of the air, the temperature of condensation and the temperature of the phase change material in Chicago, Ill.

FIG. **18** is a graph showing the annual temperatures of the air, the temperature of condensation and the temperature of the phase change material in Yuma, Ariz.

FIG. **19** shows the production gain with respect to Majuba percentage for Yuma, Ariz. and Chicago, Ill.

FIG. **20** shows a side view of a cooling system employing a moving mesh in accordance with an embodiment of the present invention.

FIG. **21** is a top down view of the cooling system shown in FIG. **20**.

FIG. **22** shows a side view of a diagram illustrating an embodiment of the moving mesh of FIG. **20**.

FIG. **23** shows a schematic view of a PCM recirculating mesh system and mesh, which employs conveyor rolls.

FIG. **24** shows another schematic view of a PCM recirculating mesh system employing conveyor rolls with an optional configuration that employs linked panels to create the mesh system.

FIG. **25** is a graph showing the pressure drop, versus the phase change material mesh wire diameter and the phase change material mesh thickness.

FIG. **26** is a diagram of the air flow across the conduit banks.

FIG. **27** is a graph of friction factor versus scaled out-of-plane spacing.

FIG. **28** is a schematic diagram of a carousel cooling system employing a rotating encapsulated phase change material structure in accordance with an embodiment of the present invention, the upper portion of FIG. **28** shows detail of diagram in the lower portion of FIG. **28**.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT(S)

For illustrative purposes, the principles of the present disclosure are described by referencing various exemplary embodiments. Although certain embodiments are specifically described herein, one of ordinary skill in the art will readily recognize that the same principles are equally applicable to, and can be employed in other systems and methods.

Before explaining the disclosed embodiments of the present disclosure in detail, it is to be understood that the disclosure is not limited in its application to the details of any particular embodiment shown. Additionally, the terminology used herein is for the purpose of description and not of limitation. Furthermore, although certain methods are described with reference to steps that are presented herein in a certain order, in many instances, these steps may be performed in any order as may be appreciated by one skilled in the art; the novel method is therefore not limited to the particular arrangement of steps disclosed herein.

It must be noted that as used herein and in the appended claims, the singular forms "a", "an", and "the" include plural references unless the context clearly dictates otherwise. Furthermore, the terms "a" (or "an"), "one or more" and "at least one" can be used interchangeably herein. The terms "comprising", "including", "having" and "constructed from" can also be used interchangeably. Unless otherwise indicated, all numbers expressing quantities of ingredients, properties such as molecular weight, percent, ratio, reaction conditions, and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about," whether or not the term "about" is present. Accordingly, unless indicated to the contrary, the numerical parameters set forth in the specification and claims are approximations that may vary depending upon the desired properties sought to be obtained by the present disclosure. At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the scope of the claims, each numerical parameter should at least be construed in light of the number of reported significant digits and by applying ordinary rounding techniques. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the disclosure are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains certain errors necessarily resulting from the standard deviation found in their respective testing measurements.

It is also to be understood that each amount/value or range of amounts/values for each component, compound, substituent or parameter disclosed herein is to be interpreted as also being disclosed in combination with each amount/value or range of amounts/values disclosed for any other component(s), compounds(s), substituent(s) or parameter(s) disclosed herein and that any combination of amounts/values or ranges of amounts/values for two or more component(s), compounds(s), substituent(s) or parameters disclosed herein are thus also disclosed in combination with each other for the purposes of this description.

It is further understood that each range disclosed herein is to be interpreted as a disclosure of each specific value within the disclosed range that has the same number of significant digits. Thus, a range of from 1-4 is to be interpreted as an express disclosure of the values 1, 2, 3 and 4.

It is further understood that each lower limit of each range disclosed herein is to be interpreted as disclosed in combination with each upper limit of each range and each specific value within each range disclosed herein for the same component, compounds, substituent or parameter. Thus, this disclosure to be interpreted as a disclosure of all ranges derived by combining each lower limit of each range with each upper limit of each range or with each specific value within each range, or by combining each upper limit of each range with each specific value within each range.

Furthermore, specific amounts/values of a component, compound, substituent or parameter disclosed in the description or an example is to be interpreted as a disclosure of either a lower or an upper limit of a range and thus can be combined with any other lower or upper limit of a range or specific amount/value for the same component, compound, substituent or parameter disclosed elsewhere in the application to form a range for that component, compound, substituent or parameter.

As used herein, the term "phase change material" or "PCM" refers to a material that has the capability of absorbing or releasing heat by undergoing a phase change or transition within a temperature stabilizing range. A temperature stabilizing range can include a specific phase change or transition temperature or a range of phase change or transition temperatures. Heat can be stored by, or removed from, a phase change material as a result of the material undergoing a phase change. Phase change materials described herein have an enthalpy of phase change of at least about 50 J/g.

As used herein, the term "encapsulated phase change material" or "EPCM" refers to a phase change material that is partially or completely enclosed by another material. For example, a phase change material encapsulated by a tube or a sphere.

Spray-Freezing of Phase-Change Materials

As shown in FIG. **1**, the present invention provides a cooling system **100** for cooling a fluid **113**. The cooling system **100** has a PCM flow system **114**, which includes a PCM container **101** housing at least one PCM **111**. The PCM container **101** has at least one conduit **104** located therein for transporting fluid **113** through the PCM **111** located within the PCM container **101**. The fluid **113** may be any fluid typically used for cooling, such as water.

An air flow chamber **116** is located above the PCM container **101** within the cooling system **100**. The air flow chamber **116** is provided with an air flow device **109** for generating air flow through the air flow chamber **116** and an outlet **108** for removing heated air from the cooling system **100**. The air flow device **109** in the embodiment shown in FIG. **1** is large fan-type object with rotating blades. However, other mechanisms may be used as the air flow device **109** in order to create the air flow. **4**

The PCM system **114** comprises an outlet **112** located at a lower portion of the PCM container **101**, at least one PCM spray nozzle **103** for spraying liquid-containing PCM droplets **110** into the air flow chamber **116**, and a pump **102** in fluid communication with the PCM spray nozzle **103** and outlet **112** of the PCM container **101**. The pump **102** moves the liquid-containing PCM from the outlet **112** to the PCM spray nozzle **103** and the PCM spray nozzle **103** sprays the liquid-containing PCM **111** into the air flow chamber **116**. The PCM outlet **112** may be located at a lower portion of the phase change material container **101**, where the phase change material **111** contains liquid phase change material **115**. In an exemplary embodiment, the PCM outlet **112** is at or near the bottom of the phase change material container **101**. However, the liquid PCM **115** may also be pumped to an elevated position in the air flow chamber **116** below the air flow device **109** and sprayed downwardly into the PCM container **101**.

For certain implementations, the PCM **111**, may be a PCM that can be a mixture of two or more materials. By selecting two or more different materials and forming a mixture, a temperature stabilizing range can be adjusted for any desired application. The resulting mixture can exhibit two or more different phase transition temperatures or a single modified phase transition temperature when encapsulated in the coated articles described herein.

Phase change materials may be broadly divided into organic phase change materials and inorganic phase change materials. Organic phase change materials, include paraffinic hydrocarbons (C_nH_{2n+2}) and fatty acids ($CH_3(CH_2)_{2n}COOH$). Other organic phase change materials include fatty alcohols, glycols, ethers, amides, fatty acid esters, linear hydrocarbons, branched hydrocarbons, cyclic hydrocarbons, halogenated hydrocarbons and combinations thereof. Alkanes (often referred to as paraffins), esters and alcohols are particularly preferred. Alkanes are preferably substantially n-alkanes that are most often commercially available as mixtures of substances of different chain lengths, with the major component, which can be determined by gas chromatography, having 10-50, or usually between 12 and 32 carbon atoms. Examples of suitable major components of alkane organic phase change materials include n-octacosane, n-docosane, n-eicosane, n-octadecane, n-heptadecane, n-hexadecane, n-pentadecane and n-tetradecane.

Suitable esters for use as organic phase change materials may comprise one or more C_1-C_{10} alkyl esters of C_{10}-C_{24} fatty acids, particularly methyl esters where the major component is methyl behenate, methyl arachidate, methyl stearate, methyl palmitate, methyl myristate or methyl laurate. Suitable alcohols for use as organic phase change materials include one or more alcohols where the major component is, for example, n-decanol, n-dodecanol, n-tetradecanol, n-hexadecanol, and n-octadecanol.

Inorganic phase change materials include salt hydrates (M_nH_2O), as well as inorganic salts such as aluminum phosphate, ammonium carbonate, ammonium chloride, cesium carbonate, cesium sulfate, calcium citrate, calcium carbonate, calcium chloride, calcium hydroxide, calcium oxide, calcium phosphate, calcium saccharate, calcium sulfate, cerium phosphate, chromic chloride, iron phosphate, lithium carbonate, lithium sulfate, magnesium chloride, magnesium sulfate, manganese chloride, manganese nitrate, manganese sulfate, potassium acetate, potassium carbonate, potassium chloride, potassium hydroxide, potassium phosphate, rubidium carbonate, rubidium sulfate, disodium tetraborate, sodium acetate, sodium bicarbonate, sodium bisulfate, sodium borate, sodium carbonate, sodium citrate, sodium chloride, sodium hydroxide, sodium nitrate, sodium percarbonate, sodium persulfate, sodium phosphate, sodium propionate, sodium selenite, sodium silicate, sodium sulfate, sodium tellurate, sodium tetraborate, sodium thiosulfate, strontium hydrophosphate, zinc acetate, zinc chloride, eutectic of Li_2CO_3 and Na_2CO_3, and combinations thereof.

Phase change materials can undergo a solid-liquid/liquid-solid phase transition at phase changing temperatures. A person skilled in the art may select the proper phase change material depending on the temperature of the fluid **113** entering and exiting the PCM container **101**. At the temperature of the fluid **113** entering the PCM container **101**, the phase change material should be essentially a liquid. In addition, at the temperature of the fluid **113** exiting the phase change material container **101**, the phase change material should also be liquid.

Referring to FIG. **2**, in some embodiments, the PCM **111** in the PCM container **101** may be a slurry of solid particles **117** and liquid PCM **115**. The provision of a slurry of phase change material **111** in the PCM container **101** offers some advantages by promoting heat transfer through the phase change material **111** and by stabilizing the temperature of the slurry. The lower portion of the phase change material **111** in the PCM container **101** will contain liquid PCM **115**.

Referring back to FIG. **1**, in some embodiments, the phase change temperature of the PCM **111** is from about 0° C. to about 100° C. below the temperature of the fluid **113** entering into the inlet **105** and passing through the PCM container **101** via the conduit **104**. In some embodiments, the phase change temperature of the PCM **111** is from about 5° C. to about 80° C. below the temperature of the fluid **113** passing into the inlet **105** and passing through the phase change material container **101** via conduit **104**. In some embodiments, the phase change temperature of the PCM **111** is from about 10° C. to about 60° C. below the temperature of the fluid **113** passing into the inlet **105** and through the phase change material container **101** via conduit **104**.

In some embodiments, the fluid **113** is steam which is passed through the conduit **104** to be condensed. The steam enters the conduit **104** through the fluid inlet **105** and exits as a liquid (such as water) through the fluid outlet **106**. In an exemplary embodiment, the steam condensation temperature is in the range of from about 20° C. to about 70° C., or from about 25° C. to about 60° C., or from about 30° C. to about 55° C., or from about 30° C. to about 50° C., or from about 35° C. to about 45° C. It has been found that at a fluid condensation temperature of about 40° C. using a phase change material, net power production can be increased, with a gain of up to 10%, in comparison with air cooled condensers.

In an another exemplary embodiment, the phase change temperature of the PCM **111** is in the range of from about 10° C. to about 60° C., or from about 15° C. to about 50° C., or from about 20° C. to about 45° C., or from about 20° C. to about 40° C., or from about 25° C. to about 35° C.

Generally, the enthalpy of phase change for the phase change of the PCM **111** is high. Suitable organic phase change materials **111** exhibit a high enthalpy of phase change, typically greater than 50 J/g, usually at least 90 J/g, preferably at least 100 J/g, more preferably greater than 120 J/g, even more preferably greater than 150 J/g and most preferably greater than 200 J/g when determined by Differential Scanning calorimetry (DSC) as measured using a Perkin Elmer DSC1 at a scan speed of 5° C./minute. This high enthalpy of phase change allows a relatively large amount of heat transfer from the fluid to the PCM **111** and from the PCM droplets **110** to the air, based on the weight of the PCM **111**, and allows use of less material to transfer the heat rendering the cooling system **100** more energy efficient.

In some embodiments, one or more types of thermal conductivity enhancers, including metal meshes, graphite foams, and nano-sized additives may be added to the PCM **111** to facilitate heat transfer to or from the PCM **111**. Metal meshes have mesh holes for enhancing thermal conductivity. The meshes have a structure in which fibers of the mesh are interwoven, such as a film or sheet provided with through holes. More details about metal meshes can be found in, for example, EP 2 612 755 A1, the disclosure of which is incorporated herein by reference in its entirety.

Graphite foams offer an integrated network for heat flow. In one embodiment, graphite foams are embedded between the conduits **104** to enhance thermal conductivity in the PCM container **101**. Such graphite foams may add drag to phase change material slurries, which may be compensated by increasing the pumping power of the pump **102**. The graphite foams are described in, for example, WO 2012/011934 A1, which is incorporated herein by reference.

In another embodiment, high thermal conductivity nano-sized additives may be added to the PCM **111**. Some examples of nano-sized additives include carbon nanotubes, carbon/graphite nanofibers, and exfoliated graphene nano-platelets (xGnP). In an exemplary embodiment, xGnP at 10 wt % loading in a phase change material, such as paraffin, can provide up to a 10-fold increase thermal conductivity. However, the viscosity of the paraffin/xGnP composite increases as the loading, f, of the xGnP, increases, thereby placing an effective upper limit on the amount of xGnP that can be incorporated into the phase change material **111**.

Suitable nano-sized additives include carbon black, other carbon-based materials, silicon carbide, carbon nanotubes (commercially available from Carbon Nanotechnologies, Inc.) and nano fibers (commercially available from Applied Sciences, Inc. of Ohio). In some embodiments, the nano-sized additives have a loading of from about 2 wt. % to about 15 wt. % of the total weight of the phase change material/nano-sized additive composition, or from about 3 wt. % to about 12 wt. %, or from about 3 wt. % to about 10 wt. % or from about 4 wt. % to about 8 wt. % or from about 5 wt. % to about 7 wt. % of the total weight of the phase change material/nano-sized additive composition.

Referring to FIGS. **1** and **2**, the PCM container **101** houses PCM **111**. The top surface of the PCM **111** held in the PCM container **101** receives solid phase change material **117** from the air flow chamber **116**. During operation, the lower portion of the PCM **111** held in the PCM container **101** contains liquid PCM **115**. In some embodiments, the combination of the solid PCM **117** and the liquid PCM **115** forms a slurry of phase change material **111** in the PCM container **101**. As shown in FIGS. **1** and **2**, at least one conduit **104** runs through the PCM container **101**, and as shown in FIG. **2** it is contemplated that a plurality of conduits **104** run through the PCM container **101**. The fluid **113** to be cooled enters the conduit **104** through a fluid inlet **105** and the cooled fluid **113** exits from the conduit **104** through fluid outlet **106**. As the fluid **113** passes through the conduit **104** in the PCM container **101**, heat is transferred from the fluid **113** through the wall(s) of the conduit **104** to the PCM **111**. As a result of the transfer of this heat, solid phase change material **117** is melted whereby a large amount of heat is absorbed as a result of the high enthalpy of phase transition of the PCM.

Referring to FIGS. **2** and **3**, in some embodiments, a plurality of conduits **104** pass through PCM container **101** to provide a greater surface area for heat transfer from the fluid to the PCM **111** held within the PCM container **101**. The conduits **104** pass through the PCM **111** in the PCM container **101**. Solid PCM **117** may be provided to the top surface of the PCM **111** in the PCM container **101**, though it is also possible to deliver the solid PCM **117** to other locations within the phase change material **111** in PCM container **101**. Thus, in operation, the phase change material **111** in the PCM container **101** typically contains a mixture of solid PCM **117** and liquid PCM **115** which may form a slurry. As a result of the heat transfer from the fluid **113** to the PCM **111**, the solid PCM **117** in the PCM container **101** undergoes a phase change to become liquid PCM **115**.

Referring to FIG. **2**, at the lower portion of the PCM container **101**, the PCM **111** includes liquid PCM **115**. Liquid-containing phase change material **111** at the lower portion of the PCM container **101** exits through an outlet **112** to enter the phase change material flow system **114**. Thus, the PCM **111** in the PCM container **101** undergoes a constant vertical flow from the top of the PCM container **101** to the bottom of the PCM container **101** and then is returned to the PCM container **101** by the phase change material flow system **114**. In the process of moving through the PCM container **101**, the PCM **111** absorbs heat from the fluid in the at least one conduit **104** and solid PCM **117** undergoes the solid-liquid phase change to form liquid phase change material **115**.

In some embodiments, the solid PCM **117** may become molten at from about 30% to about 70% of the distance from the top surface of the PCM **111** to the bottom of the PCM container **101**, or from about 40% to about 60%, or from about 45% to about 55% of the distance from the top surface of the PCM **111** to the bottom of the PCM container **101**.

In some embodiments, each conduit **104** has a diameter of from about 0.025 m to about 0.1 m, or from about 0.035 m to about 0.09 m, or from about 0.045 m to about 0.08 m, or from about 0.055 m to about 0.07 m. The distance between the conduits **104** may be from about 0.01 m to about 0.03 m, or from about 0.015 m to about 0.025 m.

Referring to FIG. **2**, the flow and thermal behavior of slurries comprising solid PCM **117** of a defined size suspended in liquid PCM **115** is explained. FIG. **2** shows a schematic representation of one embodiment of vertical flow from the top to the bottom of the PCM container **101** that passes a phase change material slurry over the assembly of conduits **104**. The overall net flow of PCM **111** towards the bottom of the PCM container **101** may be at a volume flux in a range of from about 1 mm/s to about 20 mm/s, or from about 2 mm/s to about 15 mm/s, or from about 2 mm/s to about 12 mm/s, or from about 3 mm/s to about 10 mm/s. The denser solid PCM **117** may settle through the liquid PCM **115** due to buoyancy effects as the slurry flows towards the bottom of the PCM container **101**.

In some embodiments, the thermofluidic phenomena in the PCM container **101** may be characterized by dimensionless parameters as listed in Table 1 that may be used to correlate fluid flow and heat transfer. Table 1 shows value ranges for the dimensionless control variables. In Table 1, U is the free stream volume flux entering the cylinder array, V_{Solid} and V_{Total} are the volumes of the solid particles and the total slurry, and α is the thermal diffusivity of the liquid phase PCM.

TABLE 1

Dimensionless Control Variables		
Parameter	Equation	Range
Reynolds number	Re = UD/ν	1-1200
Prandtl number	Pr = ν/α	1-100

TABLE 1-continued

Dimensionless Control Variables		
Parameter	Equation	Range
PCM volume fraction	$\phi = V_{Solid}/V_{Total}$	0.01-0.6
Diameter ratio	δ = d/D	0.01-0.4
Spacing ratio	σ = S/D	0.1-2

These dimensionless control parameters are correlated to pressure coefficient (C_P) and Nusselt number (Nu) as:

$$C_P=2\Delta P/\rho_{pcm}U^2=f_1(Re,Pr,\phi,\delta,\sigma)$$

$$Nu=h_{pcm}D/k_{pcm}=f_2(Re,Pr,\phi,\delta,\sigma)$$

$$h_{pcm}=Q/[A(T_{wall}-T_i)]$$

where ρ_{pcm} and k_{pcm} are the density and thermal conductivity of the liquid phase change material **111**, and h_{pcm} is the heat transfer coefficient of the phase change material slurry, Q is the total heat supplied by the fluid **113** entering the conduit **104**, A is the total surface area of the conduits **104**, and T_{wall} and T_i are the average conduit surface temperature and the phase change material temperature before absorbing heat from the conduit **4**, respectively. T_o is the temperature of the PCM **111** exiting the PCM container **101**, i.e. after heat absorption from the conduit **104**.

Referring back to FIG. **1**, the air flow chamber **116** is where the heat transfers from the liquid-containing phase change material droplets **110** to an air flow through the air flow chamber **116**. The air flow chamber **116** has plurality of air inlets **107** for the cool air to enter the air flow chamber **116** and an air outlet **108** for the heated air to exit the air flow chamber **116**. The air flow in the air flow chamber **116** may be from the bottom to the top of the air flow chamber **116** as shown. The air flow may be driven by an air flow device **109** in the air flow chamber **116**. The air flow device **109** may be one or more fans or any other suitable conventional apparatus.

One or more phase change material spray nozzles **103** spray fine droplets **110** of liquid-containing phase change material into the air flow chamber **116**.

Referring to FIGS. **3-5**, a droplet **110** of liquid-containing phase change material is exposed to the air flow in the air flow chamber **116**. The PCM droplets **110** provide a large surface area for transferring heat from the PCM droplets **110** to the air. As the heat is being transferred from the PCM droplets **110** to the air flow, the surface **121** of the PCM droplets **110** starts solidifying. As more heat is transferred out of the PCM droplets **110**, the PCM droplets **110** may completely solidify. In some embodiments, PCM droplets **110** may contain only liquid PCM **115** though in other embodiments, PCM droplets **110** can potentially be a slurry of a portion of solid PCM **117** in liquid PCM **115**.

The air flow in the air flow chamber **116** is controlled such that the air flow is not strong enough to carry the PCM droplets **110** out of the air flow chamber **116** through the air outlet **108**. At the exit of the phase change material spray nozzle **103**, the PCM droplets **110** have a relatively high velocity to propel the PCM droplets **110** through the air flow in the air flow chamber **116**. In this embodiment, due to the direction of spraying, the PCM droplets **110** gradually lose velocity as they travel through the air flow chamber **116** and become solidified. The air flow rate should be adjusted so as not to entrain the PCM droplets **110** and carry them out through air outlet **108**. The PCM droplets **110** eventually fall back to the surface of the PCM **111** in the phase change material container **101** which, in this embodiment, is located below the air flow chamber **116**.

The diameter of the PCM droplets **110** is in millimeters. If the size of the droplets **110** is too small, a large amount of phase change material will be lost from the cooling system **100** since small PCM droplets **110** will be carried out of the air flow chamber **116** by the air flow through the air outlet **108**. If the size of the PCM droplets **110** is too large, then there may not be sufficient surface area for transferring heat from the PCM droplets **110** to the air flow in the air flow chamber **116**. As a result, the PCM droplets **110** may not be sufficiently solidified while passing through the air flow. Thus, if the diameter of the PCM droplets **110** is too large, the heat rejection from the PCM droplets **110** to the air may not be complete and this will result in a reduction in the efficiency of the cooling system **100**.

In some embodiments, the mean diameter of the PCM droplets **110** is from about 0.5 mm to about 20 mm, or from about 1 mm to about 15 mm, or from about 1 mm to about 12 mm, or from about 2 mm to about 10 mm. The phase change material spray nozzles **103** are designed to generate phase change material droplets **110** with a narrow size distribution of, for example, ±2 mm, more preferably, ±1 mm and, most preferably, ±0.1 mm.

The phase change material spray nozzle **103** injects phase change material droplets **110** into the air flow chamber **116**. While the phase change material droplets **110** travel through the air flow in the air flow chamber **116**, they lose heat to the air flow and become solidified. The travel distance for the phase change material droplets **110** before they solidify depends on the size of phase change material droplets **110** and air flow rate in the air flow chamber **116**. When the size of the phase change material droplets **110** increases, the phase change material droplets **110** take longer to solidify, thus requiring a larger and taller air flow chamber **116**. Air flow rate increases will enhance heat transfer from the phase change material droplets **110** to the air flow, thus accelerating solidification of the phase change material droplets **110** and may reduce the size and height of the air flow chamber **16**. Therefore, smaller phase change material droplets **110** and a higher air flow rate will accelerate solidification of the phase change material droplets **110** as they travel through the air flow, thus reducing the residence time required for the phase change material droplets **110** to solidify in the air flow chamber **116**.

The one or more phase change material spray nozzles **103** spray phase change material droplets **110** into the air flow chamber **116**. The phase change material spray nozzles **103** are designed to provide droplets **110** of a desired size and may atomize the liquid-containing phase change material **111** pumped from the lower portion of the phase change material container **101**. The phase change material spray nozzles **103** spray the phase change material droplets **110** with a velocity such that the phase change material droplets **110** can travel through the air flow for sufficient time for transferring heat to the air flow and at least partially or completely solidifying the phase change material droplets **110**, before the phase change material droplets **110** are returned to the phase change material container **101**. In preferred embodiments, the phase change material droplets **110**, as they lose velocity and heat, become solidified and fall back to the top surface of the phase change material **111** in the phase change material container **101**.

In a preferred embodiment, droplets **110** of phase change material will be completely solidified upon passage through air chamber **116** prior to being returned to phase change material container **101**. Thus, it is desirable to ensure that the residence time of the phase change material droplets **110** in the air chamber **116** is sufficient to completely solidify the liquid phase change material **115** in droplets **110**. In the embodiment shown in FIG. **1**, the phase change material droplets **110** are sprayed in a generally upward direction to maximize contact time with the air flow by requiring that the droplets **110** travel both upwardly in air chamber **116** and then back downwardly in air chamber **116** thereby providing additional time to solidify the phase change material **111**. This embodiment allows use of a smaller air chamber **116** and thus a smaller cooling system **100**. Alternatively, the droplets **110** can be sprayed from the top or another location of air chamber **116** but this may require enlargement of air chamber **116** to ensure sufficient residence time of droplets **110** in air chamber **116** for the desired complete solidification of liquid phase change material **115** to occur. Typically, the phase change material droplets **110** will be sprayed at an angle of 60-120° relative to the upper surface of the phase change material **111** in the phase change material container **101**, or from 70-110° or from 80-100° or at about 90°.

It is also desirable to ensure that the solid phase change material **113** is returned to the phase change material container **101** in a manner which distributes as evenly as possible over the entire area of the phase change material **111** in phase change material container **101**. This can be accomplished, for example, by directing the spraying of phase change material droplets **110** into air chamber **116** in a manner which ensures that the droplets **110** are relatively evenly distributed over the upper surface of the phase change material **111** in the phase change material container **101** when the solid phase change material **101** returns to the phase change material container **101**. An exemplary spray pattern is shown in FIG. **1**.

In some embodiments, the air flow rate in the air flow chamber **116** is from about 10,000 kg/s to about 130,000 kg/s, or from about 20,000 kg/s to about 120,000 kg/s, or from about 30,000 kg/s to about 100,000 kg/s, or from about 40,000 kg/s to about 90,000 kg/s, or from about 50,000 kg/s to about 80,000 kg/s. In some embodiments, the air velocity in the air flow chamber **116** may be from about 4 m/s to about 14 m/s, or from about 5 m/s to about 13 m/s, or from about 6 m/s to about 12 m/s, or from about 7 m/s to about 11 m/s, or from about 8 m/s to about 10 m/s.

The size of phase change material droplets **110** is correlated with the air flow speed in the air flow chamber **116**. A faster air flow rate tends to carry phase change material droplets **110** out of the air flow chamber **116** more easily. The faster air flow rate also enhances heat transfer from the phase change material droplets **110** to the air flow. Thus, the size of phase change material droplets **110** should be increased when a faster air flow rate is used in the air flow chamber **116**. Conversely, a slower air flow rate tends to not carry phase change material droplets **110** out of the air flow chamber **116**. However, a slower air flow rate is less efficient for heat transfer from the phase change material droplets **110** to the air flow. Thus, a slower air flow rate requires smaller phase change material droplets **110** to provide more surface area for the heat transfer. A slower air flow rate also requires less power input into the air flow generation device **109**. The air flow velocity must be sufficiently high to generate a sufficient heat transfer coefficient to remove the required amount of heat.

In another aspect, the present invention provides a method as shown in FIG. **6** for operating a cooling system **100** for cooling a fluid. The method includes the steps of transferring heat from the fluid to a phase change material **111** to melt at least some solid phase change material **113** to provide liquid phase change material **115**; spraying droplets **110** of liquid-containing phase change material **111** into circulating air for cooling and solidifying at least some of the liquid phase change material **115** to provide solid phase change material **113** by heating said air to provide heated air; recycling the solid phase change material **113** to the transferring step; and removing the heated air from the cooling system **100**.

In the method, shown in FIG. **6**, in supplying step **151**, a fluid **113** to be cooled is supplied to at least one conduit **104** and passed through a phase change material container **101** for transferring heat from the fluid in the conduit **104** to the phase change material **111** in the phase change material container **101**. In liquid circulating step **152**, liquid-containing phase change material **111** is circulated from the phase change material container **101** to at least one phase change material spraying nozzle **103** for spraying liquid-containing phase change material droplets **110** into an air flow chamber **116**. In air circulating step **153**, air is circulated through the air flow chamber **116** for cooling the phase change material droplets **110**, whereby the cooled phase change material droplets **110** become solidified and solid phase change material **113** is returned to the phase change material **111** located in the phase change material container **101**.

The fluid to be cooled may be from any source of fluid that requires cooling such as fluid from a boiler that has been heated in a power plant. The fluid needs to be cooled and then cycled back to the boiler of the power plant. In supplying step **101**, the fluid is supplied to the at least one conduit **104** passing through the phase change material container **101**, where the at least one conduit **104** is bathed in a body of phase change material **111** which may be in the form of a slurry of solid phase change material **113** in liquid phase change material **115**. The heat from the fluid in the conduit **104** is transferred through the wall of the conduit **104** to the phase change material **111** in the phase change material container **101**. The absorption of heat from the conduit **104** causes a solid to liquid phase transition of the solid phase change material **113** to form liquid phase change material **115**. After heat is transferred out of the fluid to the phase change material **111**, the fluid is cooled and exits the conduit **104** through fluid outlet **106**.

The phase change material container **101** has liquid phase change material **115** at its lower portion. A pump **102** pumps liquid-containing phase change material **111** through the outlet **112** from the phase change material container **101** to the at least one phase change material spray nozzle **103** through conduit **118**.

The liquid-containing phase change material **111** in the conduit **118** may have a flow rate of from about 1,000 kg/s to about 5,500 kg/s, or from about 2,000 kg/s to about 4,500 kg/s, or from about 2,500 kg/s to about 4,000 kg/s, or from about 3,000 kg/s to about 4,000 kg/s, or from about 3,300 kg/s to about 3,800 kg/s.

The nozzle **103** sprays droplets **110** of the liquid-containing phase change material **111** of a desired size and/or size distribution, which travel through the air flow chamber **116** as shown, for example, in FIG. **1**.

The air flow in the air flow chamber **116** is generated by an air flow device **109**. The air flow device **109** may be one or more fans or any other suitable device for generating an air flow. The air flow device **109** controls the air flow rate in the air flow chamber **116**. The air flow rate may be in the range of from about 10,000 kg/s to about 130,000 kg/s, or from about 20,000 kg/s to about 120,000 kg/s, or from about 30,000 kg/s to about 100,000 kg/s, or from about 40,000 kg/s to about 90,000 kg/s, or from about 50,000 kg/s to about 80,000 kg/s.

In some embodiments, the air velocity in the air flow chamber **116** may be from about 4 m/s to about 14 m/s, or from about 5 m/s to about 13 m/s, or from about 6 m/s to about 12 m/s, or from about 7 m/s to about 11 m/s, or from about 8 m/s to about 10 m/s.

The air flow is generated by drawing cool air into the air flow chamber **116** using, for example, a device such as an air flow device **109**. The circulating air makes contact with the phase change material droplets **110**, as shown in FIG. **4**. Heat is transferred from the phase change material droplets **110** to the air flow, which warms up the air flow. After losing heat, the phase change material droplets **110** become solidified and fall back into the phase change material container **101**.

EXAMPLE 1

A cooling tower based on the parameters listed in Table 2 was simulated. Table 2 summarizes the baseline spray-freezing air cool condenser (ACC) design parameters for the steam tube, the phase change material container, the phase change material sprayers, and the air flow, as well as the fans, pumps, and atomizers used to achieve the desired parameters. As highlighted in Table 2, the calculated air-side convective heat transfer coefficient h_{air}=165 W/m^{2}K, which is about four times that of complex finned tubes in current ACCs. In addition, the total air-side heat transfer surface area provided by phase change material droplets **110** in-flight is around 440,000 m^2, equivalent to about twice the total surface area of current fin-tube ACCs with a larger footprint.

TABLE 2

Baseline air-cooled spray-freezing condenser design parameters.

Parameter	Value	Parameter	Value
HT area for steam, A_s	700,000 m^2	PCM settling time, t_{set}	80 s
Steam tube dia., d	0.065 m	Total PCM drop HT area, A_t	440,000 m^2
Steam tube spacing, δ	0.02 m	# of PCM atomizers	1000
U-value for cond., U_s	100 W/m^{2}K	PCM spray req. power, P_{sp}	200 kW
# of steam tube, N	690,000	Air flow rate, $\dot{m}_{air}$	70,000 kg/s
Steam tube length, H	5 m	Air velocity, V_{air}	9.1 m/s
Steam flow rate per tube	0.91 g/s	Air-side HTC, h_{air}	165 W/m^{2}K
Steam pressure drop	<20 Pa	U-value for air cooling, U_{air}	116 W/m^{2}K
PCM flow rate, $\dot{m}_{PCM}$	3,500 kg/s	Air Reynolds #	3200
PCM pumping power, P_{PCM}	343 kW	Air pressure drop, Δp_{air}	100 Pa
PCM liquid pipe dia, d_l	2 m	Fan power, P_{fan}	125 kW
PCM drop diameter, D	0.005 m	Fan diameter, d_{fan}	10 m
PCM drop Biot #	<0.1	Fan static pressure, p_{fan}	120 Pa
PCM drop gen. rate, N	6.7 × 10^7/s	# of fans	64

The computer simulated model based on the cooling tower described in Table 2 details the air-side heat transfer from the PCM droplets to the air flow in the air flow chamber. The spray-freezing distance for the PCM droplets in relation to the size (diameter) of the phase change material droplet is shown in FIG. **7**. The spray-freezing distance is the distance that the PCM droplet must travel before the PCM droplet solidifies. It is observed that an increase of the size of the phase change material droplet will require a larger spray-freezing distance, thus a larger and/or taller air flow chamber. The computer simulated model shows three different air flow chambers with heights of 65 m, 75 m, and 85 m. Note that, in contrast to finned-tube ACCs, the steam condensation and air-cooling are decoupled in the present invention, which allows the steam tubes be optimized independently of the air flow chamber to reduce cost and pressure drop.

Encapsulated Phase Change Materials

The spray-freezing of PCMs is able to help in the cooling of power plants, but there is a chance of contamination caused by drift when spray-freezing PCMs. Encapsulating the PCMs can help avoid spray nozzle clogging due to dust and other debris.

A solution employing encapsulated PCMs (EPCMs) may involve using a modular based EPCM lattice. This will provide high h_{air}, which involves no blow away or the use of a nozzle. The EPCM lattices can be fabricated using low cost fabrication methods, such as via the use of molds and 3D-printing. Different modules may have different T_{pcm} for the EPCMs. It is further possible to employ holographic polymerized photonic crystals as the EPCM encapsulant.

A diagram of a power plant system **200** that may employ the air-cooled EPCM heat exchanger is shown in FIG. **8**. The power plant system **200** includes a turbine **202** and a condenser **203**. Hot water is sent from the condenser **203** to the cooling tower **206**. Within the cooling tower **206** is the heat exchanger **210** that will provide cooling. Heat exchanger **201** is shown in more detail in FIG. **9**.

FIGS. **9-11** illustrate the air-cooled EPCM heat exchanger **210**. FIG. **9** shows the interior of the cooling tower **206** and the details of the heat exchanger **210**. The heat exchanger **210** comprises EPCM modules **212**. The EPCM modules **212** are comprised of lattices of individual EPCM particles **211**. As shown in FIG. **9** the EPCM lattices may form a cube shaped matrix, however it is contemplated other shapes may be formed from EPCM particles **211**, such as, for example, belts, wires, drag bodies (e.g. parachute shaped), etc. The heat exchanger **210** is designed to move EPCM modules **212** throughout the cooling tower **206**.

As shown in FIGS. **9-11** the EPCM modules **212** are interconnected via a cable **208**, or other mechanism for moving the EPCM modules **212** throughout the cooling fluid **213**. The cooling fluid **213** may be, for example, water, from the condenser **203**. The cooling fluid **213** enters the cooling tower **206** via the conduit **204**. The EPCM modules **212** are moved through the conduit **204** using the cable **208** and eventually EPCM modules **212** move through the EPCM inlet **219** into the air flow chamber **216**. The EPCM modules **212** are circulated within the airflow chamber **216** using the cable **208** and ultimately leave the airflow chamber **216** via the EPCM outlet **221**. The EPCM inlet **219** and the EPCM outlet **221** are relatively small openings, which are about 1% larger than the size of the PCM structure thereby allowing for use of a flexible material e.g. a rubber or plastic film to form a seal around the EPCM inlet **219** and the EPCM outlet **221** that can be used to limit evaporative loss via the EPCM inlet **219** and EPCM outlet **221** to about 0.0% to 0.0042%.

EPCM modules **212** are uniformly distributed in the cooling tower and may be moved using the cable **208** at a suitable speed such as about 1 m/s. The ratio of EPCM modules **212** within the cooling fluid **213** to the EPCM modules **212** within the airflow chamber **216** is about 1:20. When using EPCM modules **212**, different EPCM modules **212** having different T_{pcm} can be easily interchanged based upon the different environmental factors, such as the current weather. The EPCM modules **212** also possess ultra-high surface area as a result of being made up of lattices of micron- and millimeter-sized EPCM particles **211**. The EPCM modules **212** have greater than four times the h_{air} when compared with ACCs. The EPCM modules **212** may also be fabricated to have a porosity of greater than 98% and low drag.

Additionally, the EPCM modules **212** is low in cost, able to be made via emulsion techniques, molding techniques, 3D printing, polymerization and other techniques known to those of ordinary skill in the art. Additionally, the EPCM modules **212** are easy to transport since they are light weight and modular based.

The movement of the EPCM lattices **212** within the relatively warmer fluid **213** in the conduit **204**, melts the encapsulated cores **221** of the EPCM particles **211**. An exemplary EPCM particle **211** is shown in FIG. **12**. The melting of the core **221** removes heat from the fluid **213**. Circulation of the EPCM lattices **212** through the air flow chamber **216** re-solidifies the core **221** for the next pass through the fluid **213**.

FIGS. **15** and **16** are graphs that show the effects of different diameters of the EPCM particles **211**. FIG. **15** shows the air-side pressure drop versus the diameter of the EPCM particles **211**. Air-side pressure drop is calculated using the correlations of pressure drop over tube banks. Air-side pressure drop is calculated using the equation:

$$\Delta P_{air} = n_l f \chi \frac{\rho_{air} U_{air}^2}{2}$$

Where f is the friction factor, X is the correction factor and n_1 is the number of tube layers. FIG. **16** is a graph showing the effect of the EPCM particle diameter on the water and air heat transfer coefficients. From FIGS. **15-16**, it can be seed that a smaller diameter EPCM particle **211** reduces the fan power required (FIG. **15**) and enhances heat transfer. However, these factors must be balanced with the concern that the encapsulating material needs to be thick enough to be sufficiently strong and this may increase cost of the EPCM. The diameter of the rods within the EPCM lattice **212** may be 0.2 mm to 5 mm, more preferably 0.4 mm to 2.7 mm.

Table 3 shows some of the properties of EPCM particles obtained from Microtek.

TABLE 3

Properties of EPCM particles obtained from Microtek

Model #	Latent heat (kJ/kg)	Melting point (° C.)	Core Material	Shell material	PCM (core) concentration (wt. %)
MPCM18	163-173	18	Paraffin	Polymer	85-90
MPCM28	180-195	28	Paraffin	Polymer	85-90
MPCM37	190-200	37	Paraffin	Polymer	85-90

Using the EPCM lattice **221** to provide cooling of the fluid **213** eliminates emission issues that may occur when compared with sprayed PCMs. Encapsulated EPCM particles **211** are fixed thus eliminating emissions. Further, the EPCM is not pumped, but circulated by, for example, a conveyor, thereby reducing the power necessary to overcome frictional forces. Also, unlike the spray, there is no need for nozzles, fins or tubes in order for the EPCM particles **211** to be circulated. Instead, equipment is used to move the EPCM lattice **221** through the cooling tower **206**. Suitable equipment may include a conveyor belt, rollers, etc. EPCM particles **211** have a controllable size and no coalescence during melting. However, they have a lower latent heat of about 150 kJ/kg, as compared to the pure PCM, which has a latent heat of about 220 kJ/kg. Suitable EPCMs are commercially available from companies such as BASF, Microtek, CIBA, etc.

Table 4 shows baseline EPCM heat exchanger design parameters.

TABLE 4

Baseline EPCM heat exchanger design Parameters

Parameter	Value	Parameter	Value
Air Temperature	20° C.	Inlet water temp. to condenser	30° C.
EPCM melting point	30° C.	Exit water temp. from condenser	41° C.
EPCM particle center-center spacing	15 mm	EPCM particle solidification time (in air)	220 s
EPCM particle dia.	5 mm	Water flow rate	5583 kg/s
EPCM module dimension 1 m × 1 m × 1 m	1 m × 1 m × 1 m	Water flow velocity	0.05 m/s
EPCM module spacing	0.3 m	Water Re #	350
Water-side EPCM module #	2,500	Water-side heat transfer coefficient	2500 W/m^{2}K
Air-side EPCM module #	57,000	Air flow rate	70,000 kg/s
EPCM module velocity	1 m/s	Air flow velocity	10 m/s
Total EPCM particle #	1.76×10^{10}	Air Re #	3200
Total EPCM particle HT area	440,000 m^2	Air-side heat transfer coefficient	165 W/m^{2}K
EPCM melting time (in water)	10 s		

FIGS. **13** and **14** show a system analysis of the air-side and steam side heat transfer of a traditional air cooled condenser (ACC) and an EPCM heat exchanger. FIG. **13** shows a diagram of the air-side and steam side surface area for a traditional ACC. FIG. **14** shows an EPCM particle **211** cooled by air. In a system with a 700 MW heat load and an air temperature of 20° C. the h_{air} is about 45-50 W/m^2-K for a traditional ACC, and the h_{air} is about 165 W/m^2-K for the EPCM heat exchanger using an EPCM particle **211** with a diameter of about 5 mm. The value h_{air} is calculated as follows:

$$h_{air} = (2 + 0.6\mathrm{Re}_p^{1/2}\mathrm{Pr}^{1/3})\frac{k_{air}}{D}$$

The total EPCM particle heat transfer area is about A_t=440,000 m^2 and this parameter is preferably within the range of 400,000 m^2 to 750,000 m^2. This information demonstrates that the EPCM heat exchanger provides a significant improvement over the standard ACC.

Table 5 shows a system analysis of an EPCM heat exchanger, a PCM ACC and a traditional ACC with respect

to PCM pumping and fan power. The analysis is performed using a 700 MW heat load, a T_{air} of between 10-20° C. and 5 mm diameter EPCM particles **211**.

TABLE 5

System analysis of PCM pumping and fan power

	EPCM Heat Exchanger	PCM ACC	Traditional ACC
Total air flow rate, kg/s	35,000-70,000	35,000-70,000	32,400-45,000
Air Reynolds #	1,600-3,200	1,600-3,200	4000-6000
Air pressure drop, Pa	100-200	100-200	75-100
Air temperature rise, K	10-20	10-20	17
Fan static pressure, Pa	100-220	100-220	75-125
Total fan power, MW	5.8-11.7	5.8-11.7	7.6
Pumping power, MW	0.22	0.343	N/A
Fan diameter, m	~10	~10	~10
# of fans	100	100	100

The analysis shows that the pumping power is reduced the fan power is similar when compared to a PCM ACC. With an air pressure drop of $\Delta P \sim D_p^{3/2}$ a smaller particle size is desired.

Table 6 shows a system analysis of an EPCM heat exchanger and surface condenser, a PCM ACC and a traditional ACC based on size and cost. The table shows that there is a significant advantage of an EPCM heat exchanger and surface condenser over a PCM ACC and traditional ACC. The system employing the EPCM heat exchanger and surface condenser results in lower costs and requires no primary steam tubing. Further, the cooling tower height can be reduced to less than 20 meters. Also, there is a reduced particle emission problem as well as no nozzle clogging problem.

TABLE 6

System Analysis Size and Cost			
Parameter	EPCM heat exchanger + Surface Condenser	PCM ACC	Traditional ACC
Steam cond. temp (° C.)	45	40	55-65
# of units	1	1	40-72
Unit dimension (m^2)	75 × 75	75 × 75	12 × 12
Total footprint (m^2)	5600	5600	6,000-11,000
Equipment cost (MM$)	15-20	30-45	60-100
Total Power input (MW)	11.7	12	7.5
Production gain % (1%/3° C. cond. temp.)	3.3-6.7%	5-8.3%	

More than One PCM

An alternative embodiment of the present invention contemplates using more than PCM for the cooling system. Different PCMs will typically have different phase change temperatures. FIGS. **17** and **18** show the year round operation when using more than one PCM. The year round operation graphs convey that when using two different PCM materials by using higher temperature PCM materials the system can be operated during the summer months, when the energy production need is greatest, without sacrificing much in performance. During the winter months the efficiency of the power plant can be increased by taking full advantage of the lower condenser temperature provided by the lower melting temperature PCM. In both cases the turbine exit temperature remains constant regardless of the PCM material used.

FIG. **18** is a graph showing the year round operation of dual PCMs in terms of production gain compared to direct ACC. The production gain is measured by considering the decrease in condenser temperature and the correlation that for every 3° C. drop in condenser temperature the production gain increases by 1%, see for example Table 6. The graph illustrates that there is 4.4% production gain for Yuma and 4.8% production gain for Chicago.

PCM Recirculating Mesh System

Another embodiment of the present invention may employ a PCM recirculating mesh system **300**. FIGS. **20** and **21** show a side view and a top down view of cooling tower **306** that employs a PCM recirculating mesh **310**. The PCM recirculating mesh **310** is made of a mesh **312** comprised of PCM particles **311**. Water exiting the condenser is cooled by melting phase change material embedded inside hollow metal/polymer thin wires that are interconnected to form a highly porous mesh **312**. A plurality of meshes **312** may be layered to form a PCM recirculating mesh **310**. In the embodiment shown, the PCM particles **311** are particles that are encapsulated with a metal encapsulating material **323**. Additionally, the meshes **312** may be modular thereby allowing them to be substituted depending upon the environmental needs of area in which such meshes **312** are employed.

Each mesh **312** may be moved between the fluid **313** and the airflow chamber **316** using a cable **308**. FIGS. **23** and **24** also show a PCM recirculating mesh system **300** that employs conveyor rolls **309** to move the PCM recirculating mesh **310** through the airflow chamber **316** and fluid **313**. The conveyor rolls **309** are one suitable mechanism for moving the PCM recirculating mesh **310**. Other conventional transport systems may also be employed.

The mesh **312** cools the fluid **313** by absorbing heat from the fluid **313** thereby melting the PCM. The PCM in the mesh **312** loses heat and re-solidifies in the airflow chamber **316**. The top down view of the PCM recirculating mesh system **300**, shown in FIG. **21**, shows that recirculating meshes are provided throughout the cooling tower **306** and radiate from the center of the cooling tower **306** to the top of the cooling tower.

Table 7 shows parameters of the PCM recirculating mesh **310** and the environment within the cooling tower **306**.

TABLE 7

Values of parameters of cooling tower with PCM recirculating mesh			
Wire mesh diameter, D_w	2.7 mm	Air density, ρ_{air}	1.2 kg/s
Diameter of PCM contained in wire, D_{PCM}	1.9 mm	Air kinematic viscosity ν_{air}	1.5 × 10−5 m^2/s
In-plane spacing S	20 mm	Air velocity, U_{air}	10 m/s
Out-of-plane spacing, S_1	25 mm	Enthalpy of fusion, h_{fs}	200 kJ/kg
Porosity, ϵ	0.977	Cooling tower diameter, D_{tower}	80 m
Solidification Time, $T_{solidification}$	118 s	Cooling tower height, H_{tower}	30 m

Table 8 shows an analysis of the PCM recirculating mesh **310**.

TABLE 8

Baseline analysis for recirculating mesh					
Variable	Symbol	Value	Variable	Symbol	Value
Wire diameter	D_w	2.7 mm	Solidification time	T_{soli}	118 s
Wire thickness	T_w	0.4 mm	Melting time	T_{melt}	6 s
PCM	D_{PCM}	1.9 mm	Total PCM	n_l	150

TABLE 8-continued

Baseline analysis for recirculating mesh					
Variable	Symbol	Value	Variable	Symbol	Value
diameter			layer		
Wire in plane spacing	S	20 mm	Total mesh thickness	H_{PCM}	3.75 m
Wire out of plane spacing	S_l	25 mm	Waterside heat transfer coefficient	h_{water}	2960 W/m^{2}K
Power load	P_{total}	700 MW	Air side heat transfer coefficient	h_{air}	178 W/m^{2}K
Porosity	ϵ	0.977	Pressure drop in water side	ΔP_{water}	111.74 Pa
Air side Reynolds #	Re_{DW}	1720	Pressure drop in air side	ΔP_{air}	165.5 Pa
Footprint		80 m × 80 m			

Further analysis of the system provides the various parameters required for the PCM recirculating mesh **310**. For example, using the values taken from Table 8 the PCM flow rate can be calculated as:

$$\dot{m}_{PCM} = \frac{P_{total}}{h_{fs}} = \frac{700\text{ MW}}{200\ kJ/\text{kg}} = 3{,}500\text{ kg/s}$$

Total PCM required in the air side can be calculated as:

$$\begin{aligned} m_{PCM\_total} &= \dot{m}_{PCM} t_{solidification} \\ &= 3{,}500\text{ kg/s} \times 118\text{ s} \\ &= 4.13 \times 10^5\text{ kg} \end{aligned}$$

The PCM volume per recirculating mesh area is:

$$v_{PCM\_area} = \frac{2\pi D_{PCM}^2 s}{4}\left(\frac{1}{s}\right)^2 = 2.8 \times 10^5\text{ mm}^3/\text{m}^2$$

PCM mass per a recirculating mesh area is:

$$m_{PCM\_area} = v_{PCM\_area}\rho_{PCM} = 0.217\text{ kg/m}^2$$

The recirculating mesh thickness that is required can also derived from the various parameters provided in Table 8. The total recirculating mesh area is:

$$A_{total} = \frac{m_{PCM\_total}}{m_{PCM\_area}} = 1.9 \times 10^6\text{ m}^2$$

The recirculating mesh area per layer is:

$$\begin{aligned} A_{layer} &= \pi D_{tower} L_{screen} \\ &= \pi \times 80\text{ m} \times 50\text{ m} \\ &= 12566\text{ m}^2 \end{aligned}$$

The number of recirculating mesh layers is:

$$n_t = \frac{A}{A_{layer}} = \frac{1.9 \times 10^6\text{ m}^2}{12566\text{ m}^2} = 150$$

Thus, the thickness of the PCM mesh is:

$$H_{PCM} = n_t s_l = 150 \times 25\text{ mm} = 3.75\text{ m}$$

Reference is now made to FIGS. **25** and **26** to illustrate one method for calculating the air-side pressure drop of the PCM recirculating mesh system **300**. The cooling tower **306** and the PCM recirculating mesh **310** and their respective dimensions are given in FIG. **22**. The length of the recirculating mesh, L_{RM}=50 meters, the diameter of the cooling tower **306**, D_{tower}=80 meters, and the height of the cooling tower, H_{tower}=30 meters, are used to calculate the air-side pressure drop using the following equation:

$$\frac{\Delta P_{air}}{H_{PCM}} = 64.5\left(\frac{1-\varepsilon}{\varepsilon}\right)^2 \frac{\rho_{air} v_{air} U_{air}}{D_w^2} + 1.455\left(\frac{1-\varepsilon}{\varepsilon}\frac{v_{air}}{U_{air} D_w}\right)^{0.103} \frac{1-\varepsilon}{\varepsilon}\frac{\rho_{air} U_{air}^2}{D_w}$$

where U_{air} is the air velocity, v_{air} is the kinematic viscosity of the air and ρ_{air} is the air density.

The equation for determining volumetric porosity is:

$$\varepsilon = 1 - \frac{\pi D_w^2}{2 s s_l}$$

The air-side pressure drop ΔP_{air} is 166 Pa in this calculation. FIG. **25** shows the relationships between the diameter and thickness of the mesh and the air-side pressure drop.

Reference is now made to FIGS. **26** and **27** in discussing another method of calculating the drop in air pressure across conduit banks such as are shown in FIG. **26**. The equation used is:

$$\Delta P_{air} = n_l f \chi \frac{\rho_{air} U_{air}^2}{2}$$

In the equation above, f is the friction factor, x is the correction factor and n_1 is the number of conduit layers. The calculation is as follows:

$$P_L = \frac{s_l}{D_w} = \frac{25\text{ mm}}{2.7\text{ mm}} = 9.3$$

$$P_T = \frac{s}{D_w} = \frac{20\text{ mm}}{2.7\text{ mm}} = 7.4$$

$$\frac{P_T - 1}{P_L - 1} = 0.77\ \chi = 1.3$$

and

$$Re_D = \frac{U_{air} D_w}{v_{air}} = 1800$$

with an approximate value for f of 0.005. The approximate pressure drop across the mesh that results in a system with two perpendicular conduit banks, ΔP_{air} is 117 Pa.

The meshes **310** of the PCM recirculating mesh system **300** have a high heat capacity, a high heat transfer coefficient on both the air and water sides, a very large surface area, a low cross-flow pressure drop, and result in a low cost when compared to other systems. Compared to an existing fin-tubed air-cooled condenser (ACC), the PCM recirculating mesh system **300** reduces the dry-cooling initial temperature difference (ITD) required for operation of the system to 20° C., which makes the steam condensation temperature comparable to that of a wet cooling tower, without dissipating water to the environment. Furthermore, the low ITD dramatically improves the power production efficiency compared to current ACCs that have an ITD>35° C. Power production efficiency (eta) can be calculated by eta=1−TL/TH, where TL is the condenser temperature which is decreased relative to a typical ACC by fixing the PCM melt temperature. Also, the PCM recirculating mesh system **300** simultaneously increases both the heat transfer coefficient and heat transfer area, relative to those of complex finned tubes in current ACCs by significantly increasing the surface to area ratio. The PCM recirculating mesh system **300** has an air-side h value that is about four times the air-side h value of complex finned tubes in current ACCs. The PCM recirculating mesh system **300** also reduces the surface area and operational cost of primary steam by using indirect dry cooling to decouple steam condensation and heat rejection. Steam pathways can thus be optimized independently for reduced pressure drop and cost. Overall, the PCM recirculating mesh system **300** also reduces the capital cost and sub-freezing concerns relative to current ACC.

Compared to a spray-freezing cooling tower, the proposed PCM recirculating mesh system **300** has no particulate emissions because the encapsulated PCMs that are connected together into strong structures prevents contamination due drift loss. Furthermore, there is no need for additional air-side equipment when employing the present invention, since the absence of spray nozzles obviates potential nozzle clogging due to dust/debris. Also, the use of modular-based mesh **312** allows for different melting temperature PCMs to be substituted at different times to allow customization of the system to address different climatic conditions.

PCM Carousel

FIG. **28** is a diagram of a PCM carousel **400**. PCM carousel **400** is an alternative embodiment of a power plant cooling system. The upper portion of FIG. **28** shows detail of diagram in the lower portion of FIG. **28**. In the PCM carousel **400** a porous EPCM structure **410** is rotated throughout the cooling tower. The EPCM structure **410** may be highly porous, having a porosity of, for example, 94% to 97%. As the EPCM structure **410** rotates, warm fluid, in this example water, cascades over EPCM structure **410**. The EPCM particles **411** in the EPCM structure **410** absorb heat from the water causing the PCM material in EPCM particles **411** to melt. Cooled water is exhausted from the PCM carousel as shown. Separator walls **425** may be used to separate portions of the EPCM structure **410** to segregate water and air flows as well as minimizing drift of PCM material.

As the EPCM structure **410** rotates, ambient air is blown over the EPCM structure **410** in an airflow chamber **416**. The EPCM particles **411** will then reject heat to the ambient air and freeze.

Table 9 is a table showing a baseline analysis for the PCM carousel **400** of FIG. **28**.

TABLE 9

Analysis for PCM carrousel

Variable	Symbol	Value	Variable	Symbol	Value
Wire diameter	D_w	2.7 mm	Solidification time	T_{soli}	118 s
Wire thickness	T_w	0.4 mm	Melting	T_{melt}	6 s
PCM diameter	D_{PCM}	1.9 mm	Total PCM layer	N_l	785
Wire in-plane spacing	S	30 mm	Water side heat transfer coefficient	h_{water}	
Power load	P_{total}	700 MW	Air side heat transfer coefficient	h_{air}	178 W/m^{2}K
Porosity	ϵ	0.994	Pressure drop in water side	ΔP_{water}	
Footprint		80 m × 80 m	Pressure drop in air side	ΔP_{air}	167 Pa

It is to be understood, however, that even though numerous characteristics and advantages of the present invention have been set forth in the foregoing description, together with details of the structure and function of the invention, the disclosure is illustrative only, and changes may be made in detail, especially in matters of shape, size and arrangement of parts within the principles of the invention to the full extent indicated by the broad general meaning of the terms in which the appended claims are expressed.

What is claimed is:

1. A cooling system for cooling a fluid comprising: a heat exchanger comprising a recirculating mesh including a plurality of encapsulated phase change material meshes each including a plurality of encapsulated phase change material particles, and a cable driven by a device for moving the recirculating mesh between the fluid and an airflow chamber in a manner whereby some of said modules are positioned for heat exchange with said fluid and some of said modules are positioned for heat exchange with an air flow in said cooling system, wherein heat is transferred from the fluid to the encapsulated phase change material particles to melt at least some of the encapsulated phase change material particles to provide encapsulated liquid phase change material.

2. The cooling system of claim **1**, comprising a plurality of recirculating meshes.

3. The cooling system of claim **2**, wherein the plurality of recirculating meshes radiate from a central location within a cooling tower.

4. A cooling system for cooling a fluid comprising:

a heat exchanger including a plurality of encapsulated phase change material modules each including a plurality of encapsulated phase change material particles;

a rotating structure that rotates about a vertical axis for moving said modules in a manner whereby some of said modules are positioned for heat exchange with said fluid and some of said modules are positioned for heat exchange with an air flow in said cooling system,

wherein heat is transferred from the fluid to the encapsulated phase change material particles to melt at least some of the encapsulated phase change material particles to provide encapsulated liquid phase change material.

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